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SUMMARY TECHNICAL REPORT
OF THE
NATIONAL DEFENSE RESEARCH COMMITTEE

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SUMMARY TECHNICAL REPORT OF DIVISION 6, NDRC

VOLUME 6A

THE APPLICATION OF OCEANOGRAPHY TO SUBSURFACE WARFARE

OFFICE OF SCIENTIFIC RESEARCH AND DEVELOPMENT
VANNEVAR BUSH, DIRECTOR

NATIONAL DEFENSE RESEARCH COMMITTEE
JAMES B. CONANT, CHAIRMAN

DIVISION 6
JOHN T. TATE, CHIEF

WASHINGTON, D. C., 1946

[redacted]

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NOTES ON THE ORGANIZATION OF NDRC

The duties of the National Defense Research Committee were (1) to recommend to the Director of OSRD suitable projects and research programs on the instrumentalities of warfare, together with contract facilities for carrying out these projects and programs, and (2) to administer the technical and scientific work of the contracts. More specifically, NDRC functioned by initiating research projects on requests from the Army or the Navy, or on requests from an allied government transmitted through the Liaison Office of OSRD, or on its own considered initiative as a result of the experience of its members. Proposals prepared by the Division, Panel, or Committee for research contracts for performance of the work involved in such projects were first reviewed by NDRC, and if approved, recommended to the Director of OSRD. Upon approval of a proposal by the Director, a contract permitting maximum flexibility of scientific effort was arranged. The business aspects of the contract, including such matters as materials, clearances, vouchers, patents, priorities, legal matters, and administration of patent matters were handled by the Executive Secretary of OSRD.

Originally NDRC administered its work through five divisions, each headed by one of the NDRC members. These were:

- Division A — Armor and Ordnance
- Division B — Bombs, Fuels, Gases, & Chemical Problems
- Division C — Communication and Transportation
- Division D — Detection, Controls, and Instruments
- Division E — Patents and Inventions

In a reorganization in the fall of 1942, twenty-three administrative divisions, panels, or committees were created, each with a chief selected on the basis of his outstanding work in the particular field. The NDRC members then became a reviewing and advisory group to the Director of OSRD. The final organization was as follows:

- Division 1 — Ballistic Research
- Division 2 — Effects of Impact and Explosion
- Division 3 — Rocket Ordnance
- Division 4 — Ordnance Accessories
- Division 5 — New Missiles
- Division 6 — Sub-Surface Warfare
- Division 7 — Fire Control
- Division 8 — Explosives
- Division 9 — Chemistry
- Division 10 — Absorbents and Aerosols
- Division 11 — Chemical Engineering
- Division 12 — Transportation
- Division 13 — Electrical Communication
- Division 14 — Radar
- Division 15 — Radio Coordination
- Division 16 — Optics and Camouflage
- Division 17 — Physics
- Division 18 — War Metallurgy
- Division 19 — Miscellaneous
- Applied Mathematics Panel
- Applied Psychology Panel
- Committee on Propagation
- Tropical Deterioration Administrative Committee

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NDRC FOREWORD

As events of the years preceding 1940 revealed more and more clearly the seriousness of the world situation, many scientists in this country came to realize the need of organizing scientific research for service in a national emergency. Recommendations which they made to the White House were given careful and sympathetic attention, and as a result the National Defense Research Committee [NDRC] was formed by Executive Order of the President in the summer of 1940. The members of NDRC, appointed by the President, were instructed to supplement the work of the Army and the Navy in the development of the instrumentalities of war. A year later, upon the establishment of the Office of Scientific Research and Development [OSRD], NDRC became one of its units.

The Summary Technical Report of NDRC is a conscientious effort on the part of NDRC to summarize and evaluate its work and to present it in a useful and permanent form. It comprises some seventy volumes broken into groups corresponding to the NDRC Divisions, Panels, and Committees.

The Summary Technical Report of each Division, Panel, or Committee is an integral survey of the work of that group. The first volume of each group's report contains a summary of the report, stating the problems presented and the philosophy of attacking them and summarizing the results of the research, development, and training activities undertaken. Some volumes may be "state of the art" treatises covering subjects to which various research groups have contributed information. Others may contain descriptions of devices developed in the laboratories. A master index of all these divisional, panel, and committee reports which together constitute the Summary Technical Report of NDRC is contained in a separate volume, which also includes the index of a microfilm record of pertinent technical laboratory reports and reference material.

Some of the NDRC-sponsored researches which had been declassified by the end of 1945 were of sufficient popular interest that it was found desirable to report them in the form of monographs, such as the series on radar by Division 14 and the monograph on sampling inspection by the Applied Mathematics Panel. Since the material treated in them is not duplicated in the Summary Technical Report of NDRC, the monographs are an important part of the story of these aspects of NDRC research.

In contrast to the information on radar, which is of widespread interest and much of which is released to the public, the research on subsurface warfare is largely classified and is of general interest to a more restricted group. As a consequence, the report of Division 6 is found almost entirely in its Summary Technical Report, which runs to over twenty volumes. The extent of the work of a Division cannot therefore be judged solely by the number of volumes devoted to it in the Summary Technical Report of NDRC: account must be taken of the monographs and available reports published elsewhere.

Any great cooperative endeavor must stand or fall with the will and integrity of the men engaged in it. This fact held true for NDRC from its inception, and for Division 6 under the leadership of Dr. John T. Tate. To Dr. Tate and the men who worked with him—some as members of Division 6, some as representatives of the Division's contractors—belongs the sincere gratitude of the Nation for a difficult and often dangerous job well done. Their efforts contributed significantly to the outcome of our naval operations during the war and richly deserved the warm response they received from the Navy. In addition, their contributions to the knowledge of the ocean and to the art of oceanographic research will assuredly speed peacetime investigations in this field and bring rich benefits to all mankind.

The Summary Technical Report of Division 6, prepared under the direction of the Division Chief and authorized by him for publication, not only presents the methods and results of widely varied research and development programs but is essentially a record of the unstinted loyal cooperation of able men linked in a common effort to contribute to the defense of their Nation. To them all we extend our deep appreciation.

VANNEVAR BUSH, Director
Office of Scientific Research and Development

J. B. CONANT, Chairman
National Defense Research Committee

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FOREWORD

This volume deals with the physical properties of the medium in which subsurface warfare is waged. It is much more than an account of the oceanographic research sponsored by the Division. It is a text in which the science of physical oceanography is presented with special reference to the significant applications of that science to naval operations. Because of this, it should prove to be of wide interest to all Navy personnel.

The Division is deeply indebted to Mr. C. O'D. Iselin, Director of the Woods Hole Oceanographic Institution, not only for his willingness to undertake the task of collecting and editing the material presented in this report, but also for the fruitful participation of his institution in the research and development program of the Division.

Special acknowledgment should also be made to the contributions from the Scripps Institution of Oceanography of the University of California. The staff of that institution provided not only broad knowledge of the problems involved but also specialized knowledge of conditions in the Pacific Areas.

From the beginning this research program has received the most cordial support of the Navy. The Bureau of Ships, Hydrographic Office, and forces afloat united to assist in every way both the progress of the work and the application of the results to operations.

John T. Tate
Chief, Division 6

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PREFACE

Physical oceanography is one of the most backward of the geophysical sciences. In general it can be said that until quite recent years the physical aspects of the ocean were studied mainly as an adjunct to marine biology. The practical applications seemed to lie in fisheries problems, and the thinking of some oceanographers has been influenced accordingly. Others have been mainly concerned with the geographic approach. More recently a number of meteorologists have become interested in the circulation problem in the sea because of the several analogies with atmospheric problems.

Perhaps for these reasons one finds, on the whole, rather little in the standard oceanographic text books that is helpful in understanding the transmission of sound in sea water. The chief aim of the present volume has been to remedy this situation. It is hoped that it may be useful to those continuing with underwater acoustics to have available a simple summary of those aspects of physical oceanography which help to explain the behavior of sound in sea water. Since up to the present time rather little oceanographic research has been carried on in conjunction with acoustical studies, to those trained in the laboratory sciences this volume may seem rather elementary and none too well documented. Nevertheless, at the present stage of physical oceanography, we doubt that it would be profitable to treat the subject more exhaustively. The fact remains that our knowledge concerning the ocean is still rather superficial.

It is hoped that in the future underwater acoustics and physical oceanography will develop in close association. If the present volume does nothing more than to indicate how closely these two subjects are intertwined, it will have served a useful purpose.

C. O'D. Iselin

[redacted]

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PART I
PHYSICAL OCEANOGRAPHY AND SUBSURFACE WARFARE

Chapter 1

INTRODUCTION

As the instrumentation of warfare at sea has developed, and as these instruments are used by skillful operators from faster ships or at more nearly their extreme range, the final limitation is frequently imposed by the physical characteristics of the medium which vary both seasonally and geographically. Thus in a very real sense there is an oceanography of naval warfare.

As far as subsurface warfare is concerned, naval oceanography has already developed far enough to play a part in both operational and matériel activities. Knowledge of the sound conditions often makes it possible to use sonar gear more effectively and is sometimes a factor in deciding the proper tactical deployment of vessels. Knowledge concerning the subsurface distribution of temperature and salinity improves the diving operations of submarines and to a considerable degree affects their choice of offensive and evasive maneuvers. Oceanographic limitations have caused considerable modification of the standard procedures for operating sonar gear and have in some cases influenced its design. They have also required the development and manufacture of instruments to aid in predictions.

As time goes on, it becomes increasingly clear that just as climate and terrain affect the strategy of armies, so seasonal and geographical characteristics of the oceans must enter into the planning of the Navy. Winds, waves, and currents influence subsurface warfare, as well as aerial and amphibious operations, in ways that are new and different but no less real than the limitations they placed on the old Navies. There are particular times and places best suited to the operation of the diverse and specialized modern fighting ships, and skillful planning includes oceanography in the list of operational factors to be considered.

It is the primary purpose of this report to discuss the general principles of oceanography, particularly in relation to subsurface warfare. Special emphasis is placed on the parts of the subject that are most interesting from the practical standpoint, namely the temperature and salinity of the upper few hundred feet of water and their seasonal and geographical variations, winds and waves and their effects on sound conditions, and bottom sediments in relation to shallow-water echo ranging. However, the discussion is not limited entirely to matters of immediate practical importance since a more general knowledge of physical oceanography is essential for proper interpretation of sonar charts and bathythermograph records. The theoretical aspects of the subject are necessarily dealt with in a brief and nontechnical fashion here. For more complete treatment there are several standard textbooks of oceanography available.[1-3]

Physical oceanography has been somewhat slower to develop than the other branches of the geophysical sciences, in part because of the expense and difficulties of carrying out research on shipboard and in part because until recently it was not generally realized how many practical advantages were to be gained through increased knowledge of the physical characteristics of the ocean. It was the biological aspects of oceanography which were at first emphasized, rather than the physical.

The Germans seem to have been early aware of the potential importance of physical oceanography to modern naval operations, but it is not known at this time how far they developed the subject in relation to underwater sound transmission. It is known that during the period between the two world wars, the Deutsche Seewarte at Hamburg and the Institut für Meereskunde at Berlin were strongly supported by the government, and the German Navy had an oceanographic laboratory at Wilhelmshafen. Able staffs were assembled and German naval vessels were used in extended field surveys. One result of this active interest in oceanography on the part of the German Navy, namely an atlas of the changes in density of the water, both horizontally and vertically, was found in 1941 on a captured German submarine. This was designed primarily to guide the diving officer, but nothing so definite can be cited in connection with sound transmisson. The Japanese government has also taken an active interest in hydrological surveys.

Although in our country the Hydrographic Office had pioneered in the early development of the subject, when currents and weather at sea were more important to navigation than they are today, of recent years the further exploration of the ocean has

been left largely to private institutions. Before the present war only a very small beginning had been made by our Navy in the study of the physical factors influencing underwater sound transmission or the operation of submerged submarines. The relatively few physical oceanographers in this country were only vaguely aware of how their studies might be of interest to the Navy.

There have been four active centers of research in physical oceanography in this country during the war years: namely, the Oceanographic Unit of the Hydrographic Office, the Scripps Institution of Oceanography [SIO], at La Jolla, the Oceanographic Section of the University of California Division of War Research [UCDWR], at San Diego, and the Woods Hole Oceanographic Institution [WHOI]. As far as the oceanography of subsurface warfare is concerned, the two latter laboratories have carried out more of the research, but the interests of these four groups have been so close that it would be difficult in this report to place credit where it is due. In fact, even the personnel has been freely exchanged. In general, of course, at Woods Hole the studies have dealt particularly with the Atlantic Ocean, while for the most part at San Diego and La Jolla data from the Pacific have been analyzed.

It is perhaps worth noting in passing that oceanography is of importance to the Navy in a number of ways quite different from those discussed here and, therefore, at some of these laboratories active research has been in progress which is more or less unrelated to submarine warfare. For example, on the biological side studies have been carried out of the fouling of underwater surfaces. In mine warfare the currents and the character of the bottom sediments sometimes must be taken into account. In amphibious operations results of research on waves are important. To some extent these few examples have been cited to explain why the few qualified oceanographers available in this country at the start of the war have had to take up many and diverse studies. They have been ably assisted by scientists and technicians from related fields, but there has been too little time as yet to develop any one of the practical naval aspects of the subject as fully as is perhaps warranted.

It is therefore worth considering in this volume not only what has been done but also what problems remain unsolved. With both these aims in mind, the report begins with an account of the investigations that were undertaken to determine the effects of oceanography on subsurface warfare, the instruments that were developed, the methods of using the instruments for prediction purposes, and the ways in which these methods might be improved. It continues with a chapter on the transmission of sound in sea water and another on submarine diving problems. Since other volumes of the series deal specifically with these subjects, both are treated summarily here, giving only such facts as are needed for the practical interpretation of the oceanographic material that follows. The latter is divided into two parts. One deals primarily with the temperature and salinity structure of the ocean and its daily and seasonal changes due to heating, cooling, evaporation, and the various other physical processes that take place at the surface of the sea. The other is concerned with the effect on sound conditions of geographical and local variability of the oceans. Here are discussed ocean currents and eddies, coastal waters and bottom sediments, and special phenomena associated with winds and tides.

1.1 PREWAR INVESTIGATIONS OF THE ROLE OF REFRACTION IN UNDERWATER SOUND TRANSMISSION

As far as is known, in this country the role of refraction in echo ranging was first seriously considered in 1937 when some transmission measurements were made off Guantanamo, Cuba, accompanied by measurements of the vertical temperature structure of the water. The latter was determined by means of closely spaced mercurial thermometers. It was shown that the decrease in the speed of sound with depth, due to the decrease of temperature with depth near projector level, could sometimes cause sufficient downward refraction so that the beam passed beneath a shallow target, except at relatively short ranges. Very shortly afterwards the same idea was advanced independently at the West Coast Sound School [WCSS], San Diego. It is important to note that both off Guantanamo and San Diego the echo-ranging operations were carried out in deep water in areas where the effects of downward refraction are particularly striking. A large percentage of the earlier tests of sonar gear had been conducted in places where refraction effects were not so frequent.

In the course of the transmission measurements off Guantanamo, and during a second cruise off New

London the following summer, it became obvious that an instrument which would record temperature continuously against depth as it is lowered into the sea would have a great advantage in refraction studies over the conventional deep sea reversing thermometers of oceanography. A crude model of such an instrument was at that time being tested at the Woods Hole Oceanographic Institution. This instrument had been named the *bathythermograph* [BT] and was in fact actually used on a few occasions during the second series of transmission measurements. Modifications resulted in a somewhat improved BT which gave fair results when used from a vessel moving at 6 or 7 knots and which was used successfully for oceanographic studies.[a, 4]

1.2 DEVELOPMENT OF THE SURFACE VESSEL BATHYTHERMOGRAPH

Beginning in October 1940, the performance of the BT was further modified by WHOI working under contract with the National Defense Research Committee with the idea of using it as a naval instrument. It was then realized that for use by the surface vessels of the Navy such an instrument had to be workable at speeds of at least 12 to 15 knots, and this imposed very definite limitations on the design. It will be worth while here to discuss briefly these limitations.

First of all it was essential to have a light, rugged instrument that could utilize the sounding-lead principle of falling freely through the water in order to gain sufficient depth before the drag of the wire by which it is recovered becomes limiting. The alternative would be to give the instrument diving fins to aid in its descent, which would require in turn a heavier cable to retrieve it and a more powerful winch, thus increasing both the expense and the difficulties of handling the gear.

In order to exploit the sounding-lead principle the instrument must have a very rapid thermal response. Otherwise it could not record the vertical temperature changes accurately. This is desirable from another standpoint as well. Any instrument which is either lowered or raised at less than the maximum possible speed begins to be influenced by horizontal temperature variations. This could be overcome in part, it is true, by causing the instrument to record only as it is lowered or raised. However, the only way to be certain that the thermal element is functioning properly is to record most of both the up and the down temperature changes. Agreement between the two traces is proof that vertical and not horizontal gradients have been measured.

Another major requirement is that the temperature record must be relatively free from the effects of vibration so that very slight temperature changes with depth can be observed, especially in the upper 50 feet of the water column. This necessity practically precluded the use of diving planes. Also, it again raised the question of whether or not the instrument should be constructed to record only the down trace, since vibration is most likely to occur during the raising. It was decided that such vibration as occurred was not serious enough to offset the advantage of having both traces recorded on the slide. Since that time, however, there has been an increasing tendency to take readings at high speeds, thus increasing the vibration and sometimes making it difficult to interpret the records. Vibration is therefore the greatest weakness of the surface vessel BT discussed here, and modifications may be required.

The instrument must be used repeatedly from a relatively fast ship, making it almost impossible to have it record on deck. Insulated electric cables would never stand use on a high-speed winch. Finally, because at best there is a good chance that the wire may become fouled in the screws resulting in the loss of the instrument, it should be inexpensive and easy to manufacture. Thus a mechanical type of thermal element is almost a necessity.

These considerations and the tests carried out during the autumn of 1940 in the western North Atlantic led to a simple, rugged design which has not been essentially altered since. A Bourdon-type thermal element, which is compensated by a bimetallic strip to take care of the difference in temperature between the water inside the instrument and that through which it is passing, actuates a pen arm that records on a smoked glass slide mounted rigidly on the pressure element (Figures 1–3). The pressure element is of the bellows type, having a stiff internal spring and an accurately machined internal guide rod. The effect of increasing external pressure is to shorten the length of the bellows.

The speed of response of the thermal element is such that about 80 per cent of the full temperature range can be achieved in less than 1 second. While

[a] The instrument used in this work was the outgrowth of a preliminary model called an "oceanograph," which was built by Rossby and Lange at WHOI in 1934.

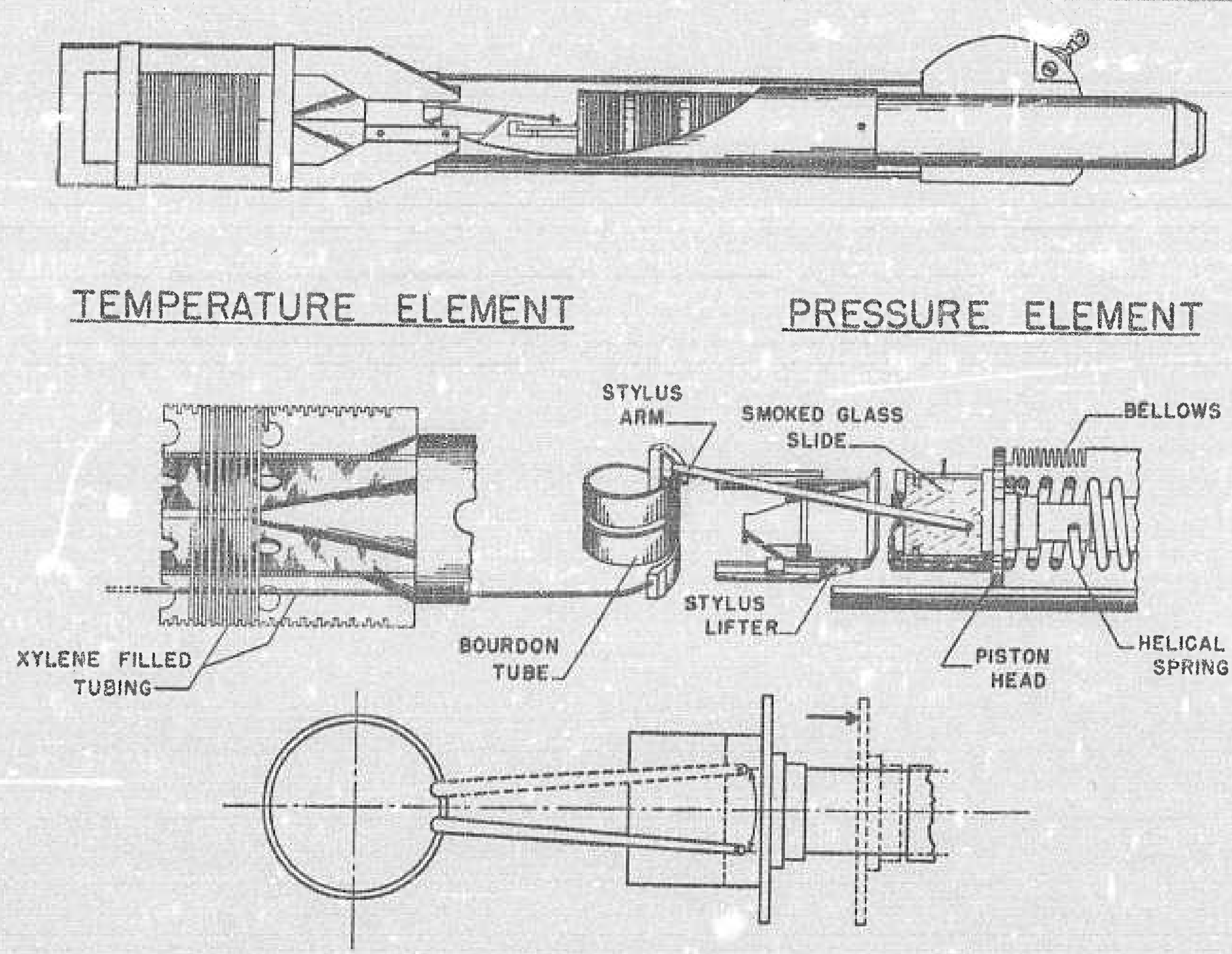

FIGURE 1. Diagram of bathythermograph.

the absolute accuracy of such a thermal system is not notably great unless it is frequently calibrated, it records vertical temperature gradients accurately enough for practical purposes when combined with a good pressure element. A rough temperature calibration can be maintained, provided the surface temperature is observed with a reliable mercurial thermometer.

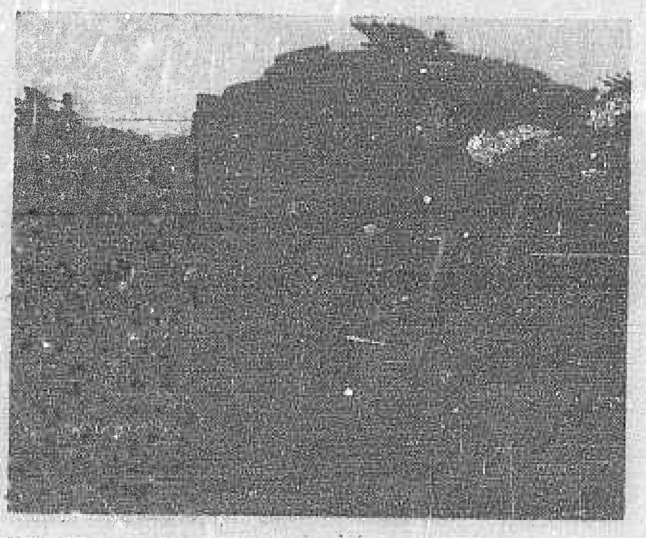

FIGURE 2. Photograph of installation.

Early in the development of the BT a basic decision had to be made. Should it record temperature against depth or, on the assumption that salinity is constant with depth, should it record the speed of sound? To have the instrument read directly in terms of the velocity of sound was obviously the direct approach to the refraction problem, yet in the end other considerations outweighed this one. Approximately 70 to 80 per cent of the time there exists near the surface a virtually isothermal layer which is stirred by convection and by the wind. However, this is not an isovelocity layer, because of the effect of pressure on the speed of sound. Thus the proper performance of the thermal element can be much better judged in

terms of temperature than in terms of velocity. Furthermore, the oceanographic aspects of sound transmission are much more easily understood in terms of temperature. As a result of this decision, the emphasis in the present report is on temperature rather than on changes in the speed of sound. At the same time it was decided to use the Fahrenheit temperature scale in accordance with Navy practice.

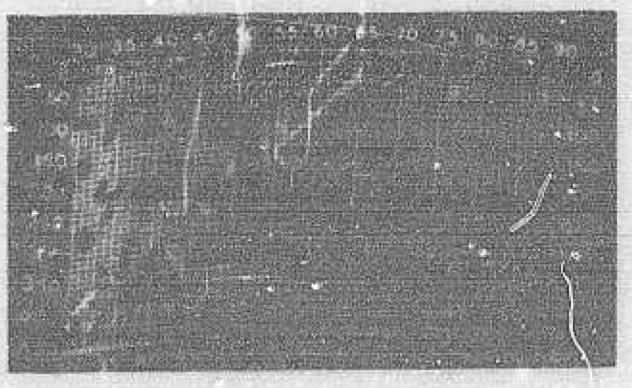

FIGURE 3. Photograph of a bathythermogram.

1.3 THE BATHYTHERMOGRAPH FOR SUBMARINES

During the course of the development of the surface vessel BT it became evident that a corresponding instrument for submarines would have several practical applications. During the summer of 1941, in response to a request by the Commander of Submarines, Atlantic Fleet, a number of temperature-depth recorders were built at Woods Hole and tested in submarines both off New London and off Key West. At first the BT for submarines was thought of primarily as an acoustic instrument. That is, it would be used to predict maximum range of the sonar equipment on the submarine, as well as the performance of her adversary's gear. However, early in the tests off Key West it became evident that vertical temperature changes could be interpreted in terms of density with sufficient accuracy to be of considerable assistance to the diving officer in maintaining proper trim. Thus a second use arose for the instrument, which has become at least as important as its original purpose.

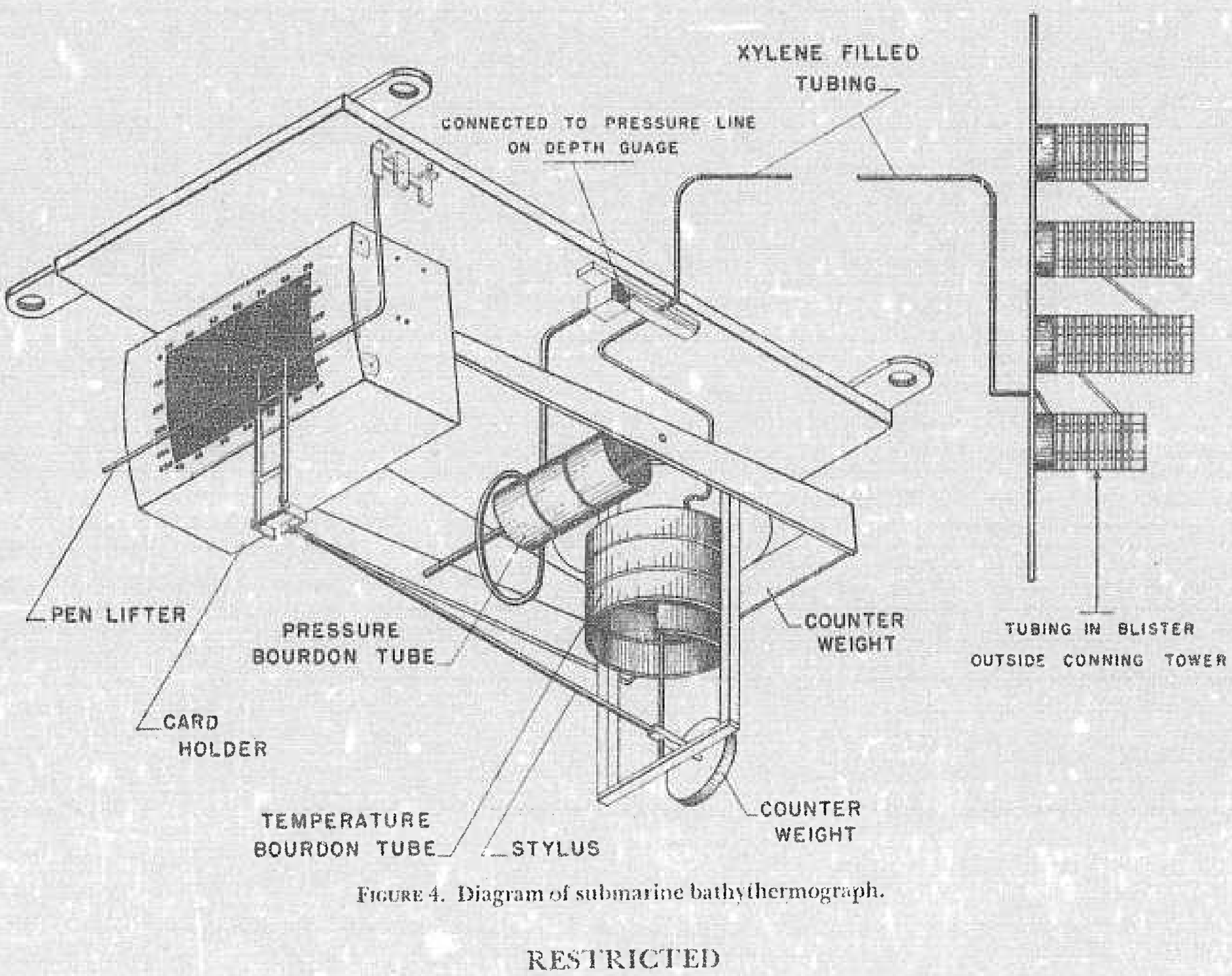

FIGURE 4. Diagram of submarine bathythermograph.

The best location for the thermal element on the hull of the submarine is still a matter to be settled by definitive tests. Locating it high on the conning tower has in the past been an acceptable compromise between a still higher position which would be preferable for acoustical purposes and a lower position which would favor diving. It is possible that two installations will be used later. Except for this question, the initial design problem of the BT for submarines was not a difficult one. It was a matter of building a sufficiently rugged and simple instrument which would fit into the available space. Again a Bourdon-type thermal element was used with suitable compensation for temperature changes inside the hull of the submarine. Another Bourdon tube was used as a pressure element by connecting it with the pressure line leading to a depth gauge. The general features of the installation are shown diagrammatically in Figure 2.

From the standpoint of subsurface warfare, the density of sea water is relatively somewhat more sensitive to changes in salinity than is the speed of sound (see Section 3.2.3). Therefore recently there has been under development a so-called salinity-compensated BT for submarines.[5] This measures temperature, salinity, and pressure, and computes and records both ballast change and the speed of sound against depth.

Chapter 2

THE DEVELOPMENT OF METHODS FOR PREDICTING SONAR AND DIVING CONDITIONS

THE early investigations of sound conditions that led to the development of the *bathythermograph* [BT] have been continued. It quickly became apparent that the whole problem of sound transmission in sea water was highly complex and that echo and listening ranges might be limited by any one of half a dozen or more factors. A great deal of fundamental research was therefore necessary before it was possible to devise a simple and accurate method of translating the basic temperature-depth curve of the BT into a practical prediction of sonar conditions.

Wartime exigencies required that as quickly as possible the results of investigations be turned into practical information for the men on the ships. Prediction methods have therefore been revised frequently as new research suggested the desirability of modifying existing methods. Proper caution was exercised in accepting such modifications, and so far only one extensive revision of official procedure has been required; nevertheless, the rapid developments in this field have resulted in some confusion, which, however unfortunate, seemed to be justified by the needs of the moment.

Aside from manuals on the operation and maintenance of the BT, official literature on the subject can be classified into two main groups:

1. Prediction manuals. These are designed so that the observer on board ship can make practical use of any particular bathythermogram by determining within certain probable limits the range that can be obtained on a submarine and can therefore operate the ship and sonar equipment according to the most efficient tactical usage for that particular range. The submariner obtains information similarly useful to him on the best depth for evasion, probable ping and listening ranges, and the most efficient diving procedure.

2. Charts. These include sonar charts showing average echo ranging conditions, average diving conditions (in the Submarine Supplements), and bottom sediment charts for shallow-water sonar work. Charts of average conditions are of less tactical value than a bathythermogram obtained at the time and place needed, because conditions are generally too variable to permit accurate enough predictions on the basis of averages. On the other hand, they provide a perspective unobtainable from a small number of bathythermograms and hence are useful not only to the observer for determining how often BT lowerings should be made, but also for more important strategic purposes.

It is beyond the scope of the present work to discuss the Navy BT literature and its scientific origins in detail. However, a more limited discussion is warranted because frequent reference will be made throughout the volume to the official literature in connection with the oceanographic part of its background. The history and the purpose of the prediction methods will therefore be described briefly. Where obvious improvements can be made, either by collection of more observations or by better use of existing data, these will be mentioned.

2.1 PREDICTION MANUALS

In February 1941 a report[1] was published summarizing what was then known about the refraction of sound in sea water and the oceanographic factors chiefly responsible. The present report is in part an expansion of the oceanographic section of this earlier study which was based largely on the experience gained at the time of the early transmission measurements previously mentioned.

Since the idea that sound is refracted in sea water in accordance with the principles of geometrical optics was not generally accepted, much of the discussion in this early report was in support of a simple refraction theory. The report was especially concerned with demonstrating that as a first approximation the vertical temperature distribution alone provided a good means of calculating the refraction pattern. Such calculations were later simplified by the introduction of a refraction slide rule,[2] and recently there has been published a collection of a large number of such calculations for the common vertical temperature distributions.[3] Another contribution was the development of the sonic ray plotter.[4]

More recent studies of the transmission of standard

sonar gear have shown that the clearly defined acoustic shadow zones which are predicted on the basis of geometrical optics are by no means always observed. Only in the case of sharp downward refraction does a marked acoustic shadow zone appear. The weaknesses of the simple refraction theory are not yet fully understood and at the time of this writing sound field measurements are still being actively secured. On the other hand, the reduction in sound intensity below a sharp thermocline, the so-called *layer effect* in echo ranging, which is predicted by the simple theory, does in fact exist. Thus no matter what the final result of the transmission studies may be, it is clear that under contemporary operating conditions vertical temperature gradients, especially when they are marked, are often the limiting factor in submarine detection. It is also clear that as the sensitivity of sonar equipment is increased and as submarines become more skillful in taking advantage of the oceanographic factors in their favor, success in subsurface warfare will depend more and more on which side has the better understanding of the medium.

According to current theories of antisubmarine and prosubmarine warfare, there are certain advantages to be gained by knowing the changes of maximum sonar range with depth. In addition, it is generally agreed that our submarines can change depth more quickly and more silently if the diving officer understands the changes in density in the superficial layers of the ocean.

Although the scientific theory of sound transmission in sea water remained undeveloped in many of its details, it gradually became possible by synthesis of the available scientific information with data on observed maximum echo ranges to work out simple schemes for range predictions that are accurate enough for practical Navy purposes. Such schemes were published in the official prediction manuals.[5, 6]

A number of problems arose in writing the manuals. In the first place, it had become clear that the refraction slide rule method of calculating acoustical ray diagrams was too ponderous and time-consuming to be of much practical value at sea. It was not enough to perform the relatively simple operation of determining the limits of the so-called shadow zone, because except in the case of strong downward refraction, the intensity of sound near the outer limit of the direct sound field was generally too low to return a detectable echo. It was necessary to go further and to calculate the distribution of intensity within the beam. This was a long task generally requiring 2 hours' work or more by an experienced calculator, and it was hardly to be recommended as a standard Navy procedure. The alternative was a method of classifying BT slides according to the most significant features of their temperature structure, such as the depth of the mixed surface layer (known as *layer depth* in Navy literature) and the strength of negative gradients near the surface and below the mixed layer. Then the probable echo range could be predicted according to simple rules for each type of temperature pattern.

Any such method has both advantages and disadvantages. The vertical temperature structure of ocean waters is at times complex, and no simple scheme for classifying it will be accurate in all circumstances. The methods in the manuals reduce such errors to a relatively low percentage but do not entirely eliminate them. In fact more careful scientific methods have thus far failed to show complete correlation between bathythermograms and observed ranges. The discrepancies are presumably due to a combination of several factors such as absorption and scattering of sound, and small and frequently changing variations in the refraction pattern that cannot be determined easily. These factors have not and perhaps never can be fully evaluated.

But even if the oceanographic variables were understood completely, it would be a mistake to suppose that maximum echo ranges could be forecast with great precision under practical circumstances. There always remain unforeseeable factors, such as target aspect and speed, that may introduce variations in maximum range of as much as plus or minus one-third of the prediction. With such large unavoidable errors in the predictions it would be fruitless to complicate the system by small and relatively insignificant refinements in refraction classification.

Moreover, a manual must take into account the fact that the predictable part of sonar performance is not always determined by water conditions. Indeed it is difficult to form an estimate of how much of the time the oceanographic factors are really limiting. If the antisubmarine vessel is a destroyer or destroyer escort and is not operating at too high a speed, if standard heavyweight sonar gear is being used, if the operator is skillful, and there is no electrical or mechanical trouble, then in deep water either the weather or the temperature distribution may become limiting. Thus oceanographic factors may be limit-

ing only a small percentage of the time or most of the time depending on the ship, its equipment, sonar personnel, and type of duty.

The non-oceanographic factors can be evaluated for any particular ship and any set of operating conditions by means of a few experiments. The current manual for the surface vessel BT (see reference 5) was intended primarily for ships of the destroyer escort class or larger, using standard heavyweight sonar equipment. The manual therefore evaluates problems of echo ranging as they apply to this particular type of vessel, with proper allowances for self noise and the effect of heavy weather in reducing ranges. It assumes that the gear is operating properly, but to make sure this is so, ways are suggested for testing its performance. Thus it is not merely a manual of refraction conditions but is a realistic approach to the whole problem of echo ranging.

The prediction manual for submarines (see reference 6) is similar in basic plan to the manual for surface ships. Prediction methods are not completely uniform, but the differences are a result of the special qualities and needs of submarines. The submarine has a much wider variety of uses for the BT than does the surface vessel. Perhaps the most important use is for predicting ballast adjustments so that diving can be accomplished as quietly as possible and with a minimum of lost time. From the standpoint of acoustics it is used to determine various things such as the best depth for evasion, ping ranges and listening ranges on surface ships, and to a lesser extent maximum echo ranges at periscope depth and at various other depths for use in evasion.

Each of these acoustical predictions is a separate problem in which refraction plays a role but is more or less modified by other factors of a non-oceanographic nature. In some respects, the submarine at periscope depth is in a more favorable position for echo ranging than a surface vessel. Self noise can be reduced to a low level, and its deep projector and its stability in heavy weather reduce quenching and pitching effects to a minimum. However, both the greatest range at which a submariner can obtain an echo from a surface vessel, and the greatest range at which he can hear the pings of a surface vessel trying to echo-range off him are affected by the speed of the surface vessel, though in different ways. Prediction of maximum listening ranges must include allowances for submarine and target ship speed as well as wind force.

The submariner's knowledge of refraction conditions and his practical utilization of them have been limited by the fact that the temperature element was mounted on the conning tower, so that at periscope depth it was impossible to determine the temperature structure in the upper 20 feet of water. Therefore, submariners have not had the knowledge that would permit them to make full use of the short periscope depth ranges that occur when there is a pronounced temperature decrease in the upper few feet. This, combined with the desirability of great depth for increased evasion time, means that in most cases a submarine will go deep when being attacked. However, new installations providing a temperature element on the periscope shears will allow more accurate determination of refraction conditions and enlarge the choice of evasive tactics.

Prediction methods presumably will be improved in many small ways in further editions of the manuals. In many cases the available information has not been so complete as might be desired. In time this situation will be corrected and the accuracy of prediction methods will be increased. There is great need for elaboration of acoustical methods in shallow water. It may very well prove impossible to predict maximum echo and listening ranges in shallow water with any degree of precision, for it is too complex a subject to resolve itself easily into a few basic rules. However, there are tactical considerations such as selection of proper receiver settings and signal length and manipulation of tilting beam that can lead to great improvements in sonar performance. Predictions for echo ranging in deep water should also be improved if possible, particularly in respect to ranges on a target at known depth. This becomes important with the advent of accurate depth-determining gear, since good predictions of range at the depth of the target will modify and improve the tactics of reattack.

Far more important than these minor revisions of existing methods are the changes and additions that must be made in order to keep abreast of current Navy developments. New gear requires careful study to determine how oceanographic factors affect its operation. Within the short space of World War II, there were several major developments in sonar equipment, and one of these in particular, the tilting beam, has created new functions for the BT which are actually more important than those for which it was originally intended. Submarine listening methods are expected to improve a great deal.

This applies both to the equipment itself and to reduction of self noise. In general, listening has not been studied nearly so thoroughly as echo ranging, and its full potentialities and the rules governing its use will not be developed for some time.

New tactics may also have oceanographic implications that are an important part of the statistical examination of their chances for success and may modify their use or determine whether or not they may be used in a particular situation. All such developments require changes in the existing manuals.

2.2 SONAR CHARTS

Early in the development of BT methods, only a few ships were equipped with the instruments and there was no possibility of making all necessary installations within less than a year or so. The need was apparent for some sort of information to aid sonar personnel in understanding the effects of oceanographic factors on echo ranging and in knowing approximately what kind of sound conditions might be expected in different parts of the oceans. The answer to this need was the sonar charts, which show average echo ranging conditions for all the oceans at different seasons of the year.

Since their beginning the charts have gone through several revisions and have changed in both their form and in the purposes for which they are used. With the increase in the number of BT installations, ships are no longer dependent on charts for all of their information on sonar conditions. However, the charts have been incorporated in the prediction procedure and are used in conjunction with the BT to determine how often lowerings need to be made, to indicate layer depth whenever tactical conditions prevent a deep lowering, and for various other purposes. They are equally applicable to submarine operations, though the Submarine Supplements discussed in Section 2.3 have in certain strategic areas replaced them with similar but more detailed information. And finally, since they are the best available information on what kind of sonar conditions can be expected at any given place and time, it is expected that the charts may serve a purpose in planning naval operations.

The construction of these charts requires a nice balance between a purely statistical analysis of the available bathythermograms and general oceanographic knowledge. The data on the winds are on the whole adequate, but the distribution of bathythermograms and oceanographic stations for any one month is still most unsatisfactory. Even when the observations from three months are combined, there are very large areas without a single observation.

If the observations were evenly scattered, both geographically and with time, a purely statistical treatment might not be seriously misleading. However, in any given area, even as large as a 5-degree square, it often happens that the available data are mostly from a single month and are not well distributed. The result is that it is still advisable to use a certain amount of art in drawing the contours, even in the case of the Northern Hemisphere oceans for which roughly 200,000 bathythermograms and oceanographic stations are now available. Except for the Southwest Pacific, there are less than 1,000 observations in all three Southern Hemisphere oceans combined. Figure 1 shows the positions where bathythermograms have thus far been obtained. Surprisingly, it has turned out that general oceanographic knowledge is on the whole adequate for this particular purpose. The charts constructed before the bathythermograms were available in quantity differed only slightly from the newest editions as far as accuracy of oceanographic information is concerned.

In successive revisions the sonar charts have gone through an evolution parallel to that of the prediction manuals. In the beginning they were based entirely on refraction, and the range contours on the charts simply represented average layer depth based on the known wind and current systems. In later editions other factors have been considered.

The charts have been expanded to contain the periscope depth range chart, and the assured range and layer depth chart. The first of these shows the average percentage of time that the periscope depth range is reduced to less than 1,500 yards by unfavorable temperature gradients near the surface of the water or by strong winds of force 7 or more on the Beaufort scale (relationship of the Beaufort scale to other velocity scales is shown in Figure 2).[a]

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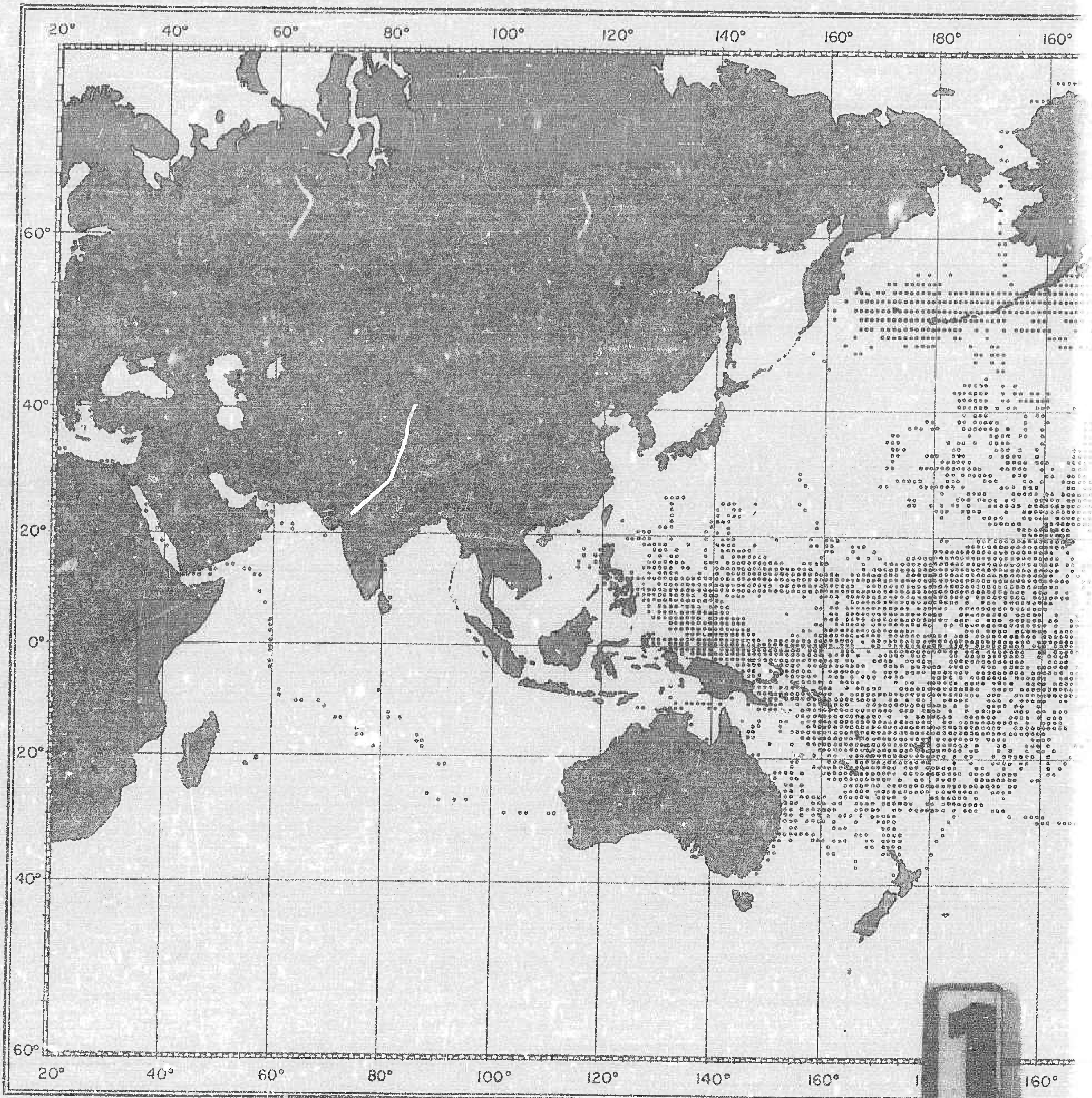
[a] The Beaufort scale was originally devised by Admiral Sir Francis Beaufort in 1805 on the basis of how much canvas a man o' war of that time could carry under different winds. An attempt to place the scale on a more objective footing was made by Dr. G. C. Simpson, whose revised scale was accepted in 1926 by the International Meteorological Committee. It is this revised scale which is presented graphically in Figure 2. It relates the Beaufort numbers to wind measurements made with an anemometer mounted in an open situation at a height of 33 feet



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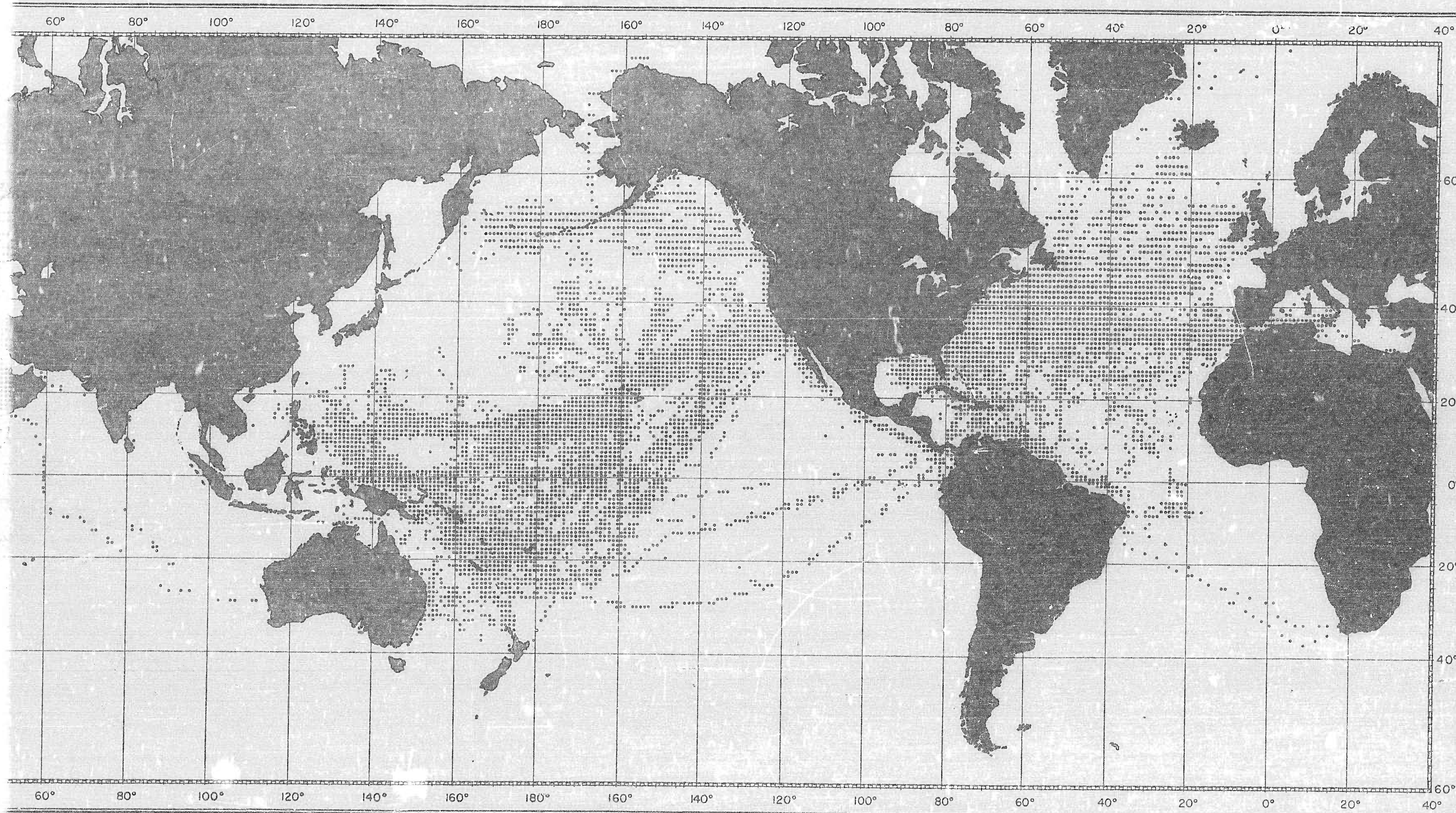

FIGURE 1. Chart showing positions where bathythermograms have been obtained.

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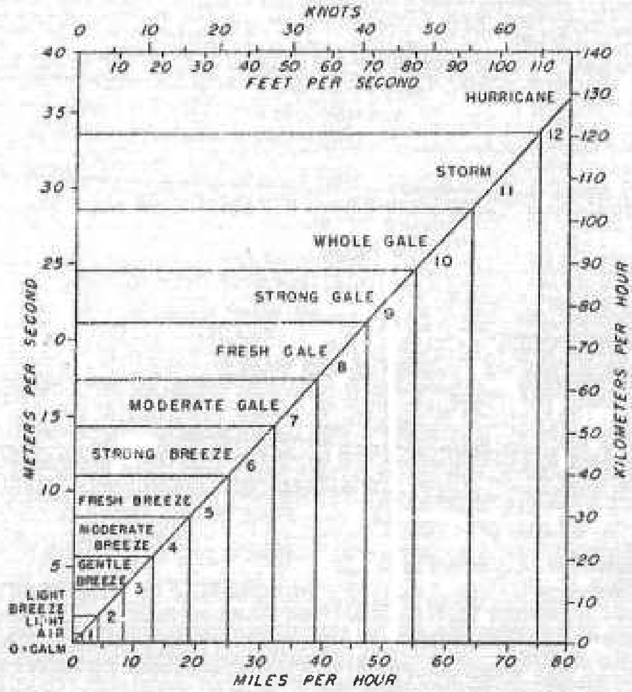


FIGURE 2. Beaufort scale of wind force compared with other velocity scales.

The assured range and layer depth chart shows the average range on a submarine which is at the best depth for avoiding detection (which may be periscope depth or just below layer depth), and it also shows the average layer depth. The range contours on this chart give the average range as indicated by temperature gradients when the wind is less than force 7. In regions where strong winds frequently reduce the assured range to less than 1,500 yards, the percentage of time this occurs is indicated. This type of chart depends primarily on large-scale oceanographic features which can on the whole be judged rather well from a knowledge of the seasonal cycle. It will be improved considerably when more is known about the details of geographical variations in the seasonal thermal cycle.

These two types of charts have been constructed for both winter and summer conditions in all the oceans. Winter in the Northern Hemisphere is defined as December through February and summer as June through August. The same months are used in Southern Hemisphere charts, but the seasons are of course reversed. For the North Pacific and North Atlantic there are also three smaller charts that show graphically the monthly variation in the average periscope depth range, assured range, and layer depth. Thus, in a general way the sonar charts show the whole seasonal temperature cycle for these areas.

Future sonar charts will be improved with the gradual acquisition of more BT records. There are very few areas in the oceans that have as yet a complete yearly cycle of BT observations, and there are very large areas where observations for only one month have been obtained. In such cases it is necessary until more records have been obtained to base the charts almost entirely on general oceanographic knowledge, wind observations, and a scattering of hydrographic stations. Collection of usable records will also be accelerated by more accurate data accompanying the bathythermograms. Without the correct position, time, and date a BT slide is useless for purposes of analysis. Many of them have been discarded because the positions were missing or obviously incorrect. Perhaps other errors not so obvious have escaped attention and have been responsible for some of the variability on the charts.

It has been apparent in the preceding discussion that sonar ranges are dependent not only on various purely oceanographic factors but also on winds, weather, and climate in general. These relationships will be discussed in some detail in the chapters that follow, although it will be seen that our knowledge about them is as yet by no means complete.

2.3 SUBMARINE SUPPLEMENTS

Submarine Supplements to the Hydrographic Office's Sailing Directions for particular areas and seasons have been issued to provide submariners with local information about diving and sound conditions. Although their general function is somewhat similar to that of the sonar charts, the scope is much broader. The Supplements contain charts of average diving and echo ranging conditions, but they also discuss the oceanography of the region in respect to effects of weather and seasonal climate, so that the usefulness of the charts is increased by providing real understanding of local conditions. Previous experience of submariners in the area is also made available

(10 meters) above sea level. The height is important, since when the air is stable (i.e., with colder air underlying warmer air) the wind velocity may vary greatly with altitude. Such a situation is common when the sea surface is much colder than the air, as off certain continental coasts in the summer time. Under such circumstances, the reading of an anemometer mounted on a naval vessel's masthead is not necessarily a reliable indication of the effective wind force by the Beaufort scale.

by including excerpts of action reports that discuss the practical utilization of existing oceanographic conditions.

The first Submarine Supplement, covering the Bay of Biscay area, was issued by the Hydrographic Office in June 1943, and it was followed shortly by a second one on late summer conditions in the Japanese Empire area. Their reception by submariners was favorable enough to justify plans for expanding the program and publishing Supplements for all areas of strategic importance.

The type of information in the different Supplements naturally has varied somewhat, depending on the oceanography of particular regions. In regard to sonar conditions, the most important feature has been data on the best depths for avoiding detection by echo ranging activities, and this has been supplemented with material on assured ranges, maximum echo ranges at periscope depth, types of bottom in shallow water areas and their sonar significance, listening conditions, and local acoustic phenomena such as biological noise. Diving problems have been emphasized somewhat more than sonar conditions. Material on this subject has included ballast changes required for diving and cruising in the area and salinity corrections to BT data.

The Submarine Supplements have not been intended for immediate tactical use. Figures on average conditions and probable variations are poor substitutes for exploratory dives, although they are useful enough when an emergency prevents such dives from being made before beginning offensive or defensive action. On the other hand, an understanding in advance of conditions and a general knowledge of the appropriate type of operations to be used proves advantageous from both the tactical and strategic standpoints. Strategy of larger scope, of planning a submarine campaign according to optimum balance between desired objectives and necessary risk will also utilize oceanography of the type discussed in the Supplements, which show the areas and seasons most favorable to submarine operation.

These publications, like the sonar charts, have been something in the nature of an experiment. It has not been certain throughout their development what information was needed most, nor were the available observations so complete as might be desired. The different Supplements have therefore been variable in quality and in manner of presentation, and revisions are needed to make them more comprehensive and more uniform in general style and content.

As in the case of prediction manuals, further developments in subsurface warfare will necessitate occasional revisions of the Supplements. Statements previously made about changes in response to modifications of sonar equipment apply equally to all these publications. Also it seems likely that submarines in the future may operate at greater depths than at present. This would require extensive revision of all charts and considerable changes in both strategy and tactics.

2.4 BOTTOM SEDIMENT CHARTS

Submarine warfare in coastal waters made it apparent early in World War II that there was great need for study of the problems of echo ranging in shallow water and the development of rules for both prosubmarine and antisubmarine forces. Accordingly, the production of bottom sediment charts was begun, which showed the distribution of different kinds of sediments with notes on the way in which they might be expected to affect sound ranging. This work was begun at a time when information on the acoustic qualities of bottom sediments was very incomplete. Indeed the whole problem of echo ranging in shallow water is a difficult one that has not yet been solved in all its details.

The different kinds of bottom that were shown on the first charts were picked more or less arbitrarily. It was known that bottom reflection and scattering could materially increase or decrease echo ranges in shallow water and that in general a smooth hard bottom extended the range, while a rough bottom shortened it. But the details of acoustical classification of these bottoms were not known, nor where the boundaries should be drawn between them. A detailed geological map would obviously be too complex for the purpose at hand, therefore it was necessary to group the many types of bottom that occur under the sea into a few general classes. As it later turned out, the choices were fortunate and, as experimental data have accumulated, only slight modifications of the range predictions have become necessary for the six major bottom types now in use.

In examining the effect of bottom structure on echo ranging, it is important first of all to consider the composition of bottom sediments. It is the texture of the sediments that largely determines how

much of the sound that reaches the bottom will be absorbed and how much will be reflected back into the water. The softer the bottom is, the more sound will be absorbed. Thus a soft mud bottom will not reflect enough sound to return an echo from a submarine, and echo ranges can be predicted, as in deep water, according to the refraction pattern. A sandy bottom, on the other hand, may reflect nearly all the sound, so that there will be little correlation between refraction and the range obtained.

In the bottom sediment charts, the criterion established for estimating the relative firmness or softness of the bottom was grain size,[b] as determined by mechanical analysis. The classification has been reasonably satisfactory from the acoustical standpoint except in the case of mud, in which it is now apparent that texture alone is not an adequate criterion. Two mud deposits with the same particle size may behave very differently with regard to the absorption of sound, one absorbing it completely, the other not at all. It is suspected, although not proved, that mud which gives some extension of range by reflection contains considerable clay, which imparts firmness to the structure. Tests of the plasticity of critical deposits are needed to determine this theory. Once the problem has been solved by a proper combination of acoustical tests and laboratory analysis, the classification can be altered accordingly. If the percentage of clay in the samples proves to be the answer, many such areas could probably be located by geological inference and this information placed on the charts.

The construction of bottom sediment charts necessitated the synthesis of material from several sources —navigational charts, oceanographic surveys, acoustical tests, and general geological knowledge of the way sediments are transported and how they are related to bottom topography. Perhaps the best way to understand how this was done is to review the history of the charts.

Prior to the war, hundreds of bottom samples and cores in all types of sediments had been taken by the Scripps Institution of Oceanography and the Woods Hole Oceanographic Institution in the course of their work in submarine geology. Mechanical analyses had been made on most of this material, so that considerable information was available for the construction of charts that could be used for acoustical work in local areas. Where coverage by actual samples was not complete enough, additional ones were immediately taken. The first bottom charts of the east coast included the easterly end of Long Island Sound, Block Island Sound, the approaches to New York, and Massachusetts Bay. These were used in experimental sound ranging by the Columbia University Division of War Research at the U. S. Navy Underwater Sound Laboratory at New London and for ambient noise surveys off New York and in Block Island Sound. On the west coast, similar charts were made for the vicinity of San Diego and San Francisco Bay and were used by the University of California Division of War Research at the U. S. Navy Radio and Sound Laboratory, San Diego, for acoustical tests of the bottom. During these charting programs, close contact was maintained between the east and west coast groups so that the classification of sediments and the methods of chart construction would be comparable in every respect.

Acoustical tests in areas such as the San Diego offing, where bottom types varied widely in relatively short distances, required great care in demarcating bottom zones and keeping within the zones during tests. In some areas where abundant bottom samples showed sand, or sand and mud, dredging revealed the presence of scattered rock ledges, and in these areas the reverberation level was distinctly higher than in other zones where such ledges did not occur. Thus it was apparent that very careful sampling was required for acoustical work on the bottom, and both dredge lines and bottom samples were needed along the course of proposed sound field runs.

In rocky areas, dredging often proved slow and laborious, and photographs of the bottom taken with an underwater camera[7] were found to be a better method. These photographs, of which examples are shown in Chapter 9, were quite adequate for the purpose when taken at closely spaced intervals, and often

[b] The size limits were set arbitrarily as follows:

- MUD — 90 per cent smaller than 0.062 mm.
- SAND AND MUD — Between 10 and 90 per cent smaller than 0.062 mm.
- SAND — Less than 10 per cent smaller than 0.062 mm and 90 per cent smaller than 2.0 mm.
- STONY — Rounded or angular pieces of rock more than 2.0 mm and less than 10 cm, which appear to represent glacial drift or other transported material.
- ROCK — Rocks of a size greater than 10 cm or pieces broken from rock ledges or where bottom photographs show projecting rocks or rock ledges.
- CORAL — Calcareous masses of coral, algae, or other lime secreting organisms, as shown by samples or bottom photographs.

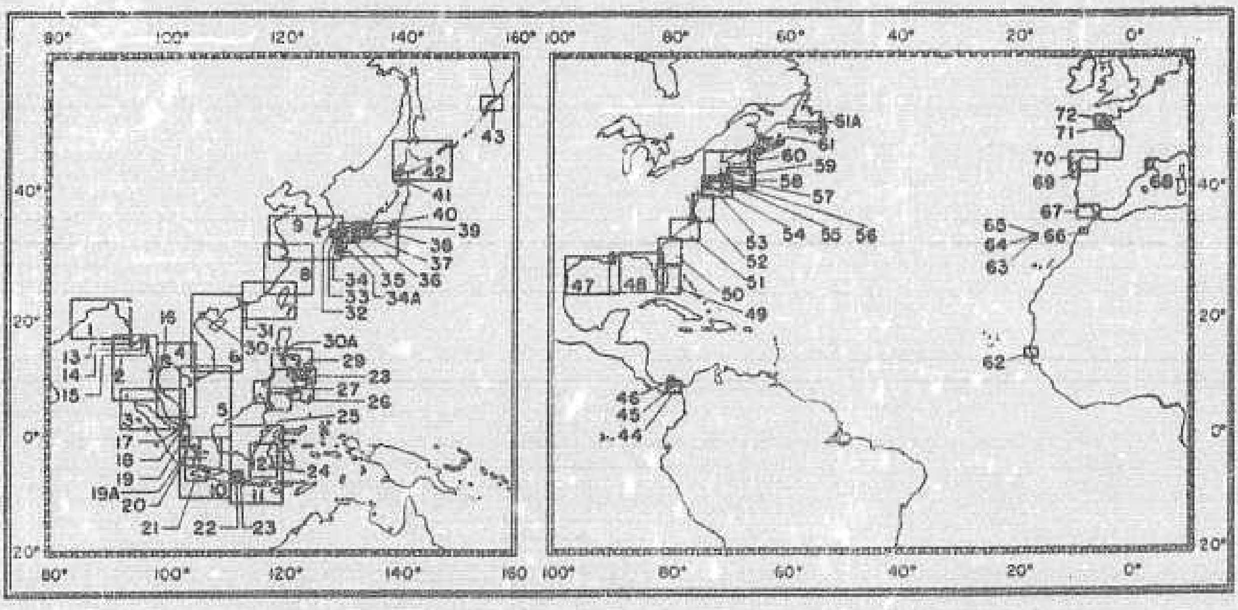


FIGURE 3. Chart showing areas covered by bottom sediment charts.

revealed useful details of bottom topography that could not be determined by bottom samples.

As soon as the preliminary program of charting and acoustical tests in local areas had progressed far enough to provide a scientific basis for further work, a general charting program was begun. Outside the areas where samples were obtainable, it was necessary to depend principally on bottom information collected during government hydrographic surveys together with the small amount of material reported in various oceanographic investigations. The surveys varied greatly from place to place in detail and reliability, depending on the importance of the region to navigation and on the country that conducted the survey. In all these cases involving transfer of information from navigational charts to charts of sound ranging conditions, judgment needed to be exercised on two counts: first, to attempt to compensate for lack of adequate information on the navigational charts by judging the situation according to what is known about particular areas that have been surveyed by more thorough methods; second, to simplify the charts by using in some cases a classification that is functionally correct from the sound ranging standpoint although not necessarily accurate geologically. The methods used in this work will be described in detail in a later chapter.

During the course of several years' work most of the important strategic areas have been charted, including the coast of the United States, the Philippines, the Japanese Islands, the east coast of China, French Indo-China, Malaya, the eastern side of the Bay of Bengal, parts of the East Indies, and selected areas off the European and African coasts. The location of these charts is shown in Figure 3.

The bottom sediment charts are used for range predictions and are incorporated in the classification schemes in the manuals. They are therefore an important part of the general tactical considerations involved in the spacing of vessels and the operation of sonar equipment so as to obtain maximum efficiency. They are equally important to submarines in the latter respect and can also be used in choosing favorable operating areas. It seems probable, however, that the full value of these charts will not be realized until work now underway has been completed. This will include not only general improvement of the charts along the lines already discussed, but also modifications of sonar equipment intended specifically to improve performance in shallow water.

Chapter 3

TRANSMISSION OF SOUND IN SEA WATER

3.1 PROPAGATION OF SOUND WAVES

Sound waves propagated in a homogeneous medium radiate outward from the source in straight lines. If the sound source is constructed so as to be directional, then most of the sound will be projected in the form of a conical beam with its axis perpendicular to the face of the projector. This situation is shown diagrammatically in Figure 1, in which A, B, and C are successive sound impulses (pings) which can be visualized as sections of the cone that constitutes the highly directional and most intense part of the emitted sound. Sound of weaker intensity will be projected at greater angles as indicated by dotted lines in the figure and will return an echo from a target at close range as indicated by the enlarged envelope of the sound impulse at A, but the greater the range the smaller will be the angular width of the effective cone, which with standard Navy sonar gear is approximately 10 to 12 degrees wide at ranges greater than 800 yards.

3.1.1 Factors Affecting Transmission

Because of divergence, the intensity of sound decreases with increasing distance from the sound source. Except for some small loss by absorption, we can assume that the total amount of energy in the sound pulse is the same at ranges A, B, and C. But as the cross sectional area of the beam increases, the amount of sound that will be intercepted and turned back by a target of unit size decreases. Since the increase in the diameter of the pulse is proportional to the range, the increase in its area is proportional to the square of the range. It follows then that within any area of constant size within the sound pulse, the intensity decrease will be inversely proportional to the square of the range.

When the sound striking a target is scattered back, then the reflected sound traveling away from the target suffers intensity loss by divergence in the same way as does the outgoing sound pulse from the projector. Therefore, in passing from target to receiver the intensity of the echo decreases as the inverse square of the range. Combining these two losses, the total decrease in intensity between the outgoing sound pulse and the echo that comes back is proportional to the inverse fourth power of the range. For every tenfold increase in range, the intensity in the direct beam will be decreased to 1/100 of its original value, and the echo intensity by the time it reaches the receiver will be reduced to 1/10,000. Absorption of sound by the water makes this decrease in sound intensity even more rapid, particularly at long ranges. All this explains why the sound of a ping at a range of 10,000 yards may be louder than an echo from a target at 1,000 yards, and why echo ranges are distinctly limited by the power of the gear. It also makes it clear that a very great increase in sound output would be required to produce a moderate increase in echo ranges.

The strength of an echo depends on the size of the target as well as on range. Thus a large vessel returns a stronger echo than a small one, and for a ship of any given size the beam aspect presents a better target than bow or stern.

These are a few of the simple properties of sound

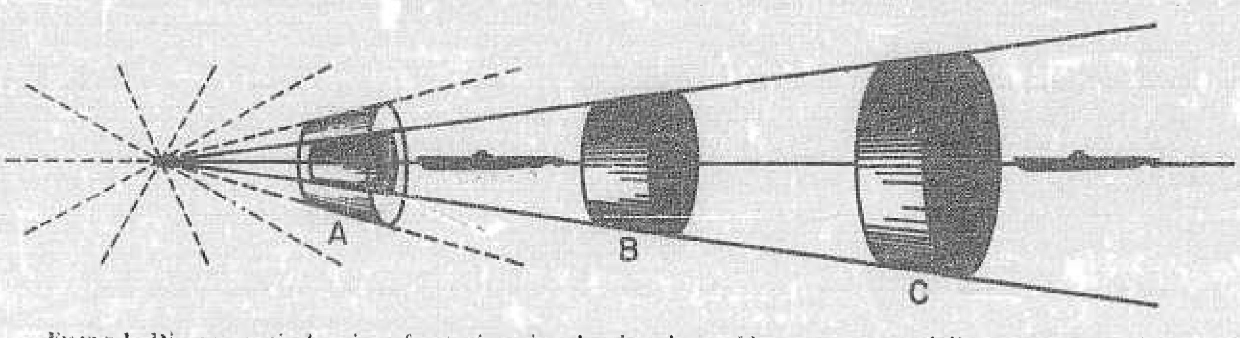


Figure 1. Diagrammatic drawing of outgoing ping showing shape of beam pattern and divergence of sound rays.

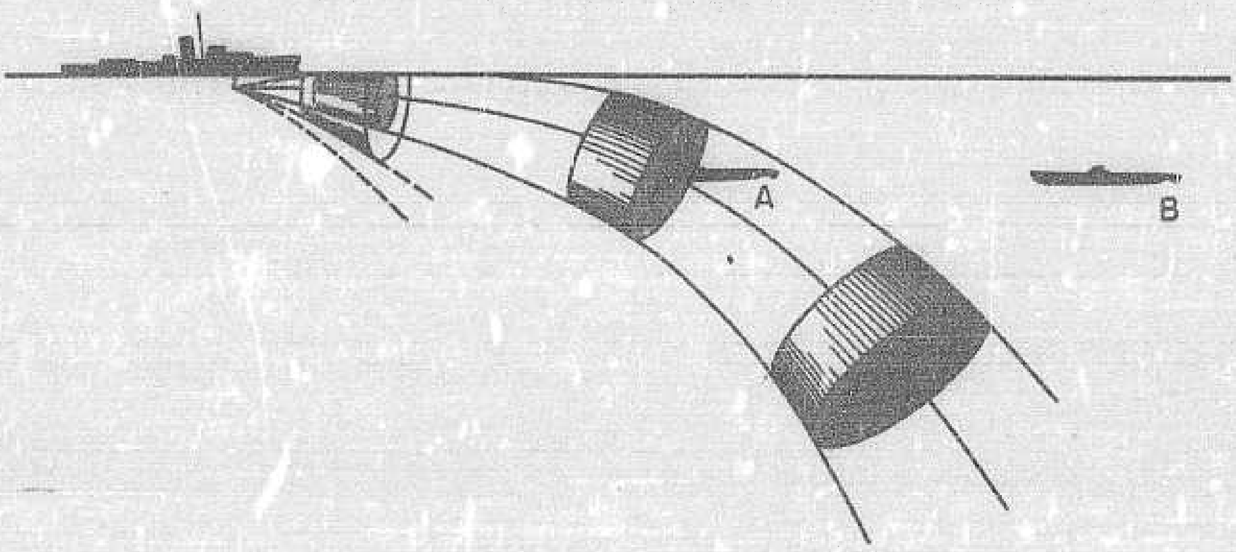


FIGURE 2. Diagrammatic drawing of outgoing ping showing effect of refraction.

transmission in a homogeneous medium. However, the sea is far from homogeneous and, moreover, in echo ranging the source of the sound is quite near the surface, which complicates the situation by reflecting and scattering sound. The physical characteristics of sea water—its temperature and salinity, the number and size of the particles suspended in it, and the disturbances of its surface—vary widely from place to place and from time to time. All these affect transmission, and underwater sound is therefore subject not only to expected divergence and absorption, but also to varying degrees of refraction, reflection, and scattering.

Reflection

Reflection occurs both from the ocean bottom and from the underside of the sea surface. If these surfaces are smooth, extension of range may result through reinforcement of the direct sound beam. If they are rough, sound will be scattered in all directions, and that part which is returned to the location of the original sound source, thereby interfering with echo recognition, is known as reverberation. The bottom effects are important enough to be regarded as the controlling factor in echo ranging wherever the depth of water is less than about 100 or 200 fathoms. Surface reflection and scattering are usually less significant in standard echo ranging. However, at short ranges (less than 1,000 yards) reverberation from the surface forms the principal background in echo ranging and may be the controlling factor in the detection of small objects whenever the sea is not calm.

Refraction

Variations in the temperature and salinity of sea water can profoundly affect sound transmission because they produce variation in the speed of sound as it travels from one point to another, and this in turn causes refraction of sound waves. It was shown in the introductory chapters how discovery of this phenomenon led to the development of the *bathythermograph* [BT] and accompanying prediction methods as instruments of naval warfare. At this time it is worth-while to discuss the principles of the simple refraction theory as it was first developed, since it provides an adequate framework for the essential facts on underwater sound transmission and the way in which maximum echo and listening ranges are affected by temperature gradients. It should be kept in mind, however, that while the theory is in approximate agreement with the most important observed results, subsequent experiments have shown it to be an incomplete explanation. Discussion of these later modifications of the refraction theory is beyond the scope of the present work but will be taken up in other volumes of the Summary Technical Report of Division 6.

Sound waves travel in straight lines only in a medium in which the speed is everywhere constant. In sea water the speed of sound generally varies with depth. Suppose, for example, the speed increases with depth. In that case every ray of the sound beam will be curved toward the surface. The more rapid the change of speed with depth, the more strongly the rays will be curved. This bending of the sound rays is

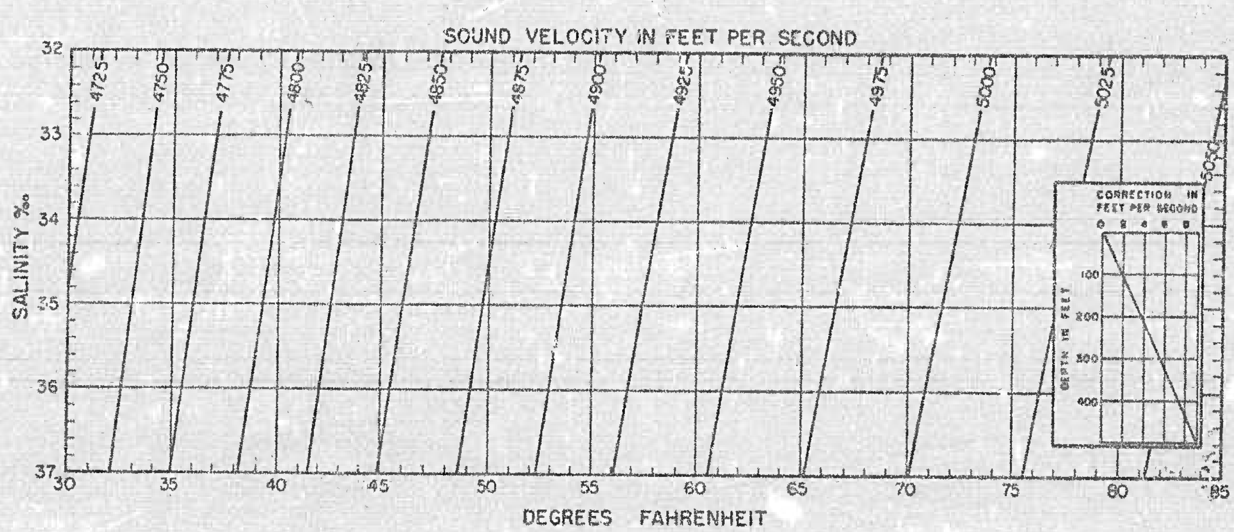


FIGURE 3. Effect of temperature, salinity, and pressure on the speed of sound in sea water.

called refraction. It will aid in understanding refraction to imagine that the lower part of the beam, in the example just cited, keeps getting slightly ahead of the upper part, because of the slight difference in speed in the water at the levels at which the two parts of the beam travel. It is a fundamental law of wave motion that the rays, which indicate the direction of travel, are always perpendicular to the wave fronts. A wave front is the surface occupied by the front of a sound signal at any instant. Because the lower part of the wave front keeps gaining on the upper, the beam will curve upward.

If the speed decreased with depth, the beam would bend downward. Refraction always causes a sound ray to shift its course toward the water in which the speed is lower. This condition is illustrated in exaggerated form in Figure 2.

Velocity of Sound

The speed of sound in sea water depends on the temperature and composition of the water. In general these quantities vary both horizontally and vertically, but only the latter is of any great significance. While horizontal changes in the speed of sound will cause changes in the time required for a signal to travel between two points, this effect is small and never serious in echo ranging. But changes in velocity with depth, even slight ones due to warming of the surface water on a bright, calm day, deflect the sound beam from the horizontal plane and may cause it to overshoot or undershoot the target.

In echo ranging work, in which only the upper few hundred feet of water are involved, temperature is generally the most important factor causing variations in sound velocity. The chemical content of sea water, of which salt is the major constituent and the only one which need be considered, is relatively uniform in the open ocean and is therefore less important than temperature in determining sound velocity. Furthermore, as will be shown later, in layers where vertical salinity gradients exist there is nearly always also a vertical temperature gradient. Another minor factor is pressure, which increases proportionally with depth. The effect of these three variables on the speed of sound is shown in Figure 3. It will be noted that they all change the velocity in the same direction. An increase in temperature, salinity, or depth (pressure) causes an increase in the velocity of sound.

Gradients

In sound transmission the vertical velocity gradient is more important than the velocity itself, since it is the change in velocity with depth that determines how much refraction will take place. The velocity gradient is readily determined from the gradients of salinity and temperature. The salinity gradient is defined as the rate of increase of salinity with depth, in parts per thousand (‰) per foot. The temperature gradient is the rate of increase of temperature with depth, in degrees Fahrenheit per foot. These gradients are therefore called positive if the quantity in question increases with depth, negative if it decreases.

It will be seen later that in the great majority of cases temperature gradients in the sea are zero or negative. Moreover, except in certain localized areas

temperature gradients control the sound velocity gradients. With a zero gradient in temperature (mixed layer), echo ranges are long because the sound rays are very nearly straight, having only a slight upward curvature due to the pressure effect. On the other hand, with a strong negative gradient near the surface, echo ranges will be short because the sound beam is refracted sharply downward. In the ocean it is common to find a mixed layer overlying a negative temperature gradient. In such cases the echo range on a target in the mixed layer will be long, but the part of the sound beam that enters the negative gradient will be refracted downward, resulting in reduction of range.

There are two phenomena which may cause reduction of range by refraction. With a strong negative temperature gradient from the surface downward, each ray of the sound beam curves down in a great arc, and beyond the horizontal limits of the beam is a so-called shadow zone into which no sound penetrates other than by scattering. An echo-ranging vessel will not be able to detect a target in the shadow zone, but as soon as the latter comes within the direct beam the echoes will come in loud and clear. This is the situation illustrated in Figure 2, in which the submarine at A is in the direct beam and the one at B is in the shadow zone.

With slighter negative temperature gradients and generally with any gradient underlying a mixed layer, the shadow zone is not very clearly defined. But downward refraction at any depth below projector level exaggerates the normal divergence of sound rays. And since the intensity of sound within the beam is inversely proportional to the divergence of the sound beam, refraction under these conditions has the effect of reducing echo intensity and thereby reducing the range. Thus a target in the negative gradient beneath a mixed layer may be within the direct beam but still be undetectable because the echoes are too weak to be heard against the background of reverberation and ship's noise. This is known as *layer effect*.

Bottom Effects

As stated previously, sound transmission in shallow water is complicated by bottom effects. Wherever the depth is greater than 200 fathoms, the bottom can be neglected in echo ranging. In contrast, where the water is less than 100 fathoms deep, the bottom sediments frequently become the limiting factor in determining maximum range. Between the 200-fathom contour and the 100-fathom contour is a zone of uncertainty as far as the effect of the bottom is concerned. However, the bottom usually slopes so steeply between these two contours that only a small fraction of the ocean area is involved.

What makes the situation particularly difficult in shallow water is that both the texture of the sediments and the topography of the bottom are acoustically important. The bottom scatters some sound back toward the source, giving rise to reverberation above which the echo must be recognized, and it may also act as an efficient reflecting surface for extending sound into areas where the intensity would otherwise be too low to return an echo. Thus a smooth, hard bottom can increase the maximum range over what would be expected under the same refraction conditions in deep water, but a rough bottom may cause such loud reverberation that the echo cannot be recognized.

Variations in echo and reverberation intensity resulting from multiple reflections frequently result in the so-called *skip distance effect*. Contact may first be established at relatively long ranges through bottom-reflected sound, but at medium ranges where the direct sound beam strikes the bottom, reverberation may be strong enough to mask the echo. Then at short ranges the echo level may be higher than the reverberation level, and contact will be regained. If the target is close to the bottom, skip distances are uncommon. Such a target will be struck by the sound beam at approximately the same range at which the bottom is struck as well. Thus, maxima in echo strength may be expected at the same ranges at which the bottom reverberation will also be strong. If the reverberation is strong enough to mask the echo at one particular range, it will mask the echo at all longer ranges as well. Whether bottom reverberation is strong enough to mask an echo depends primarily on the bottom material, and also on the depth of the water, the strength of the echo, and the refraction pattern. The range at which masking by reverberation is first likely to occur is equal to about four to six times the depth of the water, provided that strong negative temperature gradients are present. The range over which such masking may persist for a shallow target will vary, depending in part on the sediment, but commonly it is about 500 to 700 yards.

When the water is isothermal to the bottom, the range at which masking by reverberation is first likely is more nearly ten times the water depth.

Except over soft mud bottoms, which absorb nearly all the sound reaching them, or where there is strong upward refraction, layer effect is absent or much reduced in shallow water because the low intensity parts of the direct sound field are more or less filled with bottom-reflected sound.

Other Factors

False echoes are relatively frequent in shallow water, although well-trained operators should nearly always be able to classify them correctly. False echoes may be of several varieties: echoes from schools of fish, bottom irregularities, or wrecks, and sharp local rises in the reverberation level under conditions of strong downward refraction.

The ambient noise level will vary in shallow water, not only because of noise of biological origin and noise from waves, but also depending on the proximity to the shore, especially if the surf is heavy. In addition, the noise level will depend somewhat on the reflecting qualities of the bottom.

Therefore, in general it can be concluded that sound conditions in coastal waters are highly variable and tend to be poor except over a smooth, sandy bottom. These factors have in general been favorable to submarines. Since shipping must converge off the main ports and since much cargo is carried coastwise, it is frequently possible for submarines to lie in wait in particular areas that are oceanographically suitable. These advantages are partly offset by the fact that effective air coverage is more easily maintained near land; nevertheless, submarine activity could continue in coastal waters, especially where favorable oceanographic factors coincide with a high density of shipping. It is apparent therefore that both pro-submarine and antisubmarine groups must recognize and understand the problems of range prediction in shallow water.

These, then, are the major factors involved in the transmission of sound in sea water. The BT fills the obvious need for an instrument to measure the temperature gradients in the water. The prediction manuals serve to convert this information into a form that is tactically usable. However, there always remains the question of how long the observed conditions will remain reasonably constant, or to put it another way, how often BT readings will be required and what sound conditions are likely to be the next day and the day after. These questions are partially answered by the sonar charts, but the latter are of limited value in the same way that a chart of average weather conditions is limited in its value for predicting the weather tomorrow. Use of the charts and of BT predictions in general will therefore be much improved if it is tempered by judgments based on some understanding of physical oceanography and weather and the interrelations of both with sound conditions. The basic principles of this knowledge will be summarized in Parts 2 and 3.

Chapter 4

SUBMARINE DIVING PROBLEMS

4.1 INTRODUCTION

In the chapters that follow there are numerous references to submarine diving problems in connection with particular oceanographic conditions. Before the development of the submarine *bathythermograph* [BT], the submariner had no method for determining quickly and easily the oceanographic characteristics of the waters in which he was operating. Diving and maintaining trim at the desired depth were largely a matter of trial and error and were therefore costly in time and effort. The diving rules developed in connection with the BT have greatly simplified these operations. The whole subject is covered in detail in Volume 6B of Division 6. In the meantime the subject will be outlined broadly by way of introduction to oceanographic considerations discussed in other chapters of this volume.

A submerged submarine has two methods of changing depth, which may be used singly or together. First, it can change its buoyancy by regulating the amount of sea water in its ballast tanks. Flooding ballast makes the submarine less buoyant so that it sinks; pumping ballast makes it more buoyant, and it rises. Second, the elevation of the diving planes can be changed so that as the submarine moves through the water it planes up or down. A modification of this method is to ballast unequally fore and aft. The hull then lies at an angle in the water, and the planing effect is produced without changing the diving planes.

It is of the greatest importance in submarine operation to be able to change depth efficiently. It often takes an appreciable amount of time to flood or pump the requisite amount of water. During offensive or defensive operations a delay of a few minutes caused by faulty judgment as to the correct ballast change may be costly. The noise involved in diving operations is also an important consideration when operating among enemy ships that may be maintaining a listening watch.

With these considerations in mind, it is evident that optimum efficiency in diving operations means achieving the best possible balance between speed in completing the change in depth and quietness of operation throughout. It implies knowledge beforehand of what ballast changes will be needed and when, so that the submarine will not at any time become dangerously out of trim and require a sudden burst of speed or other noisy operation to keep it under control.

4.2 DENSITY LAYERS

Maintaining efficient diving operations would be simple if the buoyancy of sea water were everywhere uniform. Since it is not, the variations in density that occur make each dive a separate problem requiring slightly different tactics. These are considered briefly below.

If, for example, the submarine is in trim at periscope depth, its overall density is approximately the same as that of the surrounding sea water. Consequently, it has no great tendency either to rise or sink, and such small movements as occur are readily corrected with slight changes in the angle of the diving planes. As the vessel travels at periscope depth it may move into water of greater or less density. An increase in temperature makes the water expand so that it is lighter. The density also depends on its salt content (see Section 5.1). Such changes in density require reballasting to bring the submarine back into trim. However, these lateral density changes are relatively slight in most cases, and it requires no great effort to keep the vessel on a horizontal course.

If a submarine in trim at periscope depth dives in water of uniform density, it gradually gets out of trim because the increasing pressure at greater depths compresses the hull, making the submarine less buoyant. Therefore under these conditions a submarine must pump ballast during the dive in order to maintain trim. The amount of water to be pumped out depends on the size of the submarine and on its compressibility, the latter varying with the type of construction and, to a lesser extent, with individual vessels.

The case above is one of the rarer examples of a diving operation, because the water is not often of uniform density down to the maximum depth of submarine operation.

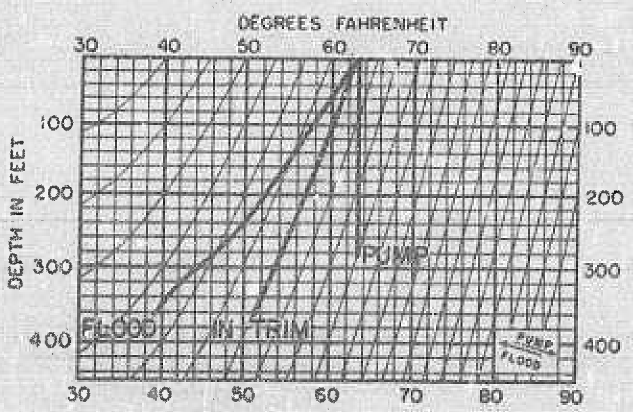


FIGURE 1. Submarine bathythermogram showing effect of temperature gradients on ballasting operations.

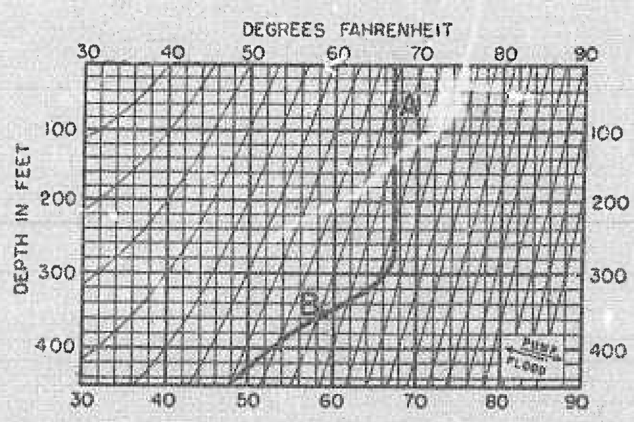


FIGURE 2. Submarine bathythermogram showing diving operations in a mixed layer with an underlying negative gradient.

4.3 TEMPERATURE VARIATIONS

It was pointed out in the introduction that the temperature may decrease from the surface downward or in the water underlying a mixed surface layer. With decreasing temperature the density would increase downward. The sea may be thought of as a series of horizontal layers one below another, in which the density is either uniform or increases downward by a greater or lesser amount.

A layer of increasing density gives a diving submarine more support and tends to counteract the compression effect. It is conceivable that the two effects may just balance, so that a diving submarine will remain in trim all the way down. On the submarine BT card (Figure 1) are printed isoballast lines, which show the amount of temperature change with depth that will, by its effect on the density of the water, exactly balance the compression effect of a submarine of the type for which the card was prepared. In any layer where the temperature-depth trace parallels the isoballast lines, the diving submarine will remain in the same state of trim throughout the layer. If the temperature is more nearly uniform, so that the trace crosses the isoballast lines toward the right, a diving submarine will get heavier and will have to pump ballast to regain trim. In a strong gradient that crosses toward the left, it will be light and will have to flood ballast.

As is already apparent from previous discussions, it is common to find temperature conditions in the sea of the kind shown in Figure 2, in which there is a surface layer of mixed water and an underlying layer with a sharp decrease in temperature. Suppose a submarine is in trim at periscope depth (Position A) and makes a dive with no ballast changes. As it goes through the mixed layer it gets heavier and sinks more rapidly. But the temperature gradient below gives it more buoyancy again, and it finally comes to trim at Position B, where the temperature trace intersects the same isoballast line that passed through Position A. This is an example of a very quick and efficient dive that makes full use of a knowledge of the temperature conditions. It would be much less efficient to dive in trim, pumping while in the mixed layer and flooding again below it. However, if there were no temperature gradient below the mixed layer, it would be more efficient as well as safer to remain more or less in trim all the way down. Thus, the correct diving procedure depends on knowledge of the vertical temperature structure of the water. The example described above is unusually simple since it is not commonly possible to dive without making any ballast changes at all. Nevertheless, the general principle holds in almost any case, that it is possible to dive more efficiently in water of known temperature structure than in an unknown situation because when the diving officer knows the total amount of ballast change that will be needed, he can make the proper adjustments at an even rate through the entire operation and will not be stopped by a sharp density gradient or forced to increase the noise output of the submarine in the effort to get through the layer. The time thus saved during a dive may be as much as 10 or 15 minutes.

In order to obtain proper knowledge of the temperature structure of the water, it is necessary for the submarine to make frequent exploratory dives. Density conditions are best dealt with in an emergency

if a recent BT record is available. How often such dives are needed depends on the variability of temperature conditions where the submarine is operating, and for this purpose sonar charts and Submarine Supplements provide the submariner with information about local variability. In offensive and defensive operations, however, this information about average layer depth is obviously less useful than the more complete and specific knowledge obtained by a recent exploratory dive.

The use of BT records for the control of diving makes no allowance for vertical density changes due to salinity structure. Throughout the greater part of the deep oceanic regions variability of salinity is an insignificant factor, but there are local areas, particularly in shallow water, where it is important. In such places temperature records must be used with discretion and supplemented where possible by salinity data in the Submarine Supplements or by general oceanographic knowledge of the kind described in subsequent chapters and dealt with more specifically in the volume on diving control previously referred to. More adequate information can be obtained by the use of the salinity-compensated BT. Whether or not it will be useful enough to justify installing such a complicated and bulky instrument will perhaps depend on the location of future strategic areas.

Further reference to the salinity-compensated BT may be found in Section 1.3 on "The Bathythermograph for Submarines."

4.4 PROGRESS OF FOREIGN NATIONS

It is not known whether foreign nations have developed diving control to the same degree as our own Navy, but it can at least be assumed that they understand the advantage of making use of density layers and have charts of average conditions similar to those in the Supplements. This much, as stated previously, has been determined from a captured German submarine, and the usefulness of density layers is too obvious to escape any submariner. For them it is a fortunate coincidence that from both the acoustic and diving standpoints density layers provide the best possible protection in evasion. The so-called "layer effect" has been mentioned, which reduces the echo and listening ranges on a submarine submerged well below the top of a density layer. It is also apparent that a submarine in the middle of such a layer requires little effort to maintain constant depth. If it rises it will be in water of less buoyancy and will tend to sink again. If it goes deeper it will encounter more buoyant water. Hence, it is not only easy to maintain quiet operation, creeping, or balancing with the motor stopped, but also it is easier to maintain control of the ship during a depth-charge attack.

PART II
TEMPERATURE AND SALINITY OF OCEAN WATERS

Chapter 5

THE BASIC VERTICAL THERMAL STRUCTURE OF THE OCEANS

5.1 THE PRIMARY SUBDIVISIONS

Although in this report we are concerned only with the physical characteristics of the water down to the greatest depth in which a submarine can operate, it is advisable at the outset to consider briefly the vertical structure of the water column as a whole. The main ocean basins average some 2,500 fathoms (15,000 feet) in depth. Until recently submarines seldom descended to depths greater than 500 feet, but the lower limit may now be approaching twice this depth. Nevertheless, in the open ocean even 1,000 feet is only a small fraction of the depth of the whole water column.

From many standpoints, the upper one or two thousand feet is the most interesting part of the ocean. It is the part that is most affected by winds and weather, by seasonal changes in temperature, and by geographical variations in climate. The surface waters of the ocean are therefore highly variable. This variability presents many problems of joint interest to the science of oceanography and to the practical applications of oceanography to subsurface warfare.

By contrast the deep waters of the ocean are static. The most violent storms have little effect at depths greater than about 1,500 feet. Seasonal and geographical variations are slight. But speaking in the absolute sense, no part of the ocean is completely static. Water movement in the great depths takes place as a very slow drift of a large mass of water, in contrast to the more rapid and localized surface currents, but large volumes of water are transported by this means. Such movements are directly related to interchanges between surface and deep water, which in turn play a part in determining the temperature pattern of the upper water. Therefore, it is hardly possible to understand either vertical temperature structure or oceanic circulation without considering to some extent the ocean as a whole.

The basic thermal structure of the ocean is illustrated in its simplest form in Figure 1, which is typical of winter conditions in mid-latitudes. It is essentially a three-layered system: a relatively warm and shallow surface layer which has very nearly the same temperature as the air above it, and which is stirred by the wind so that the temperature changes little with depth; a very deep mass of much colder water in which temperature decreases very slightly and uniformly with depth; and a third layer of transition between, known as the main thermocline. The term thermocline in oceanography is used for any layer in which temperature decreases markedly with depth. This is a stable situation, that is to say, density also increases with depth.

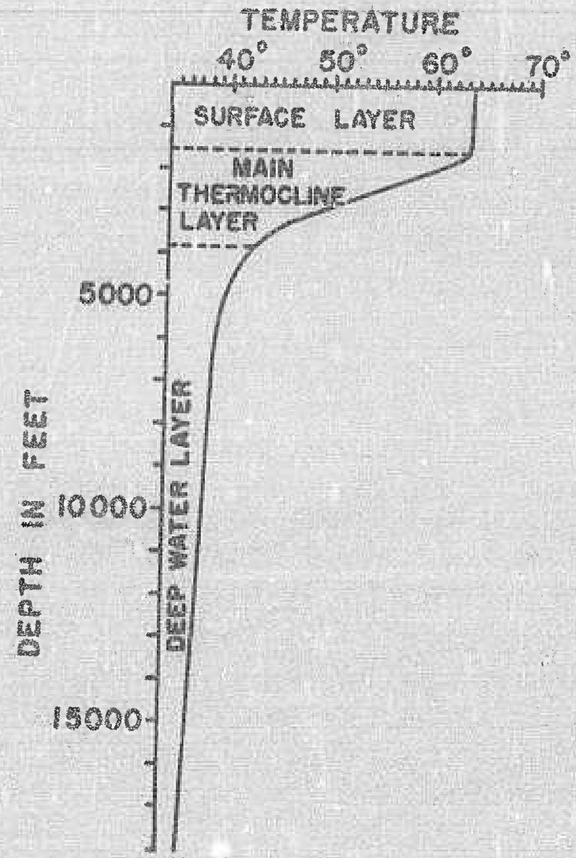


Figure 1. Basic thermal structure of the ocean—typical winter conditions in mid-latitudes.

The concept of stability as a function of the density appears frequently in any discussion of oceanography, and it is important to understand just what is involved. The density of sea water is dependent on its temperature, salt content, and the pressure of the

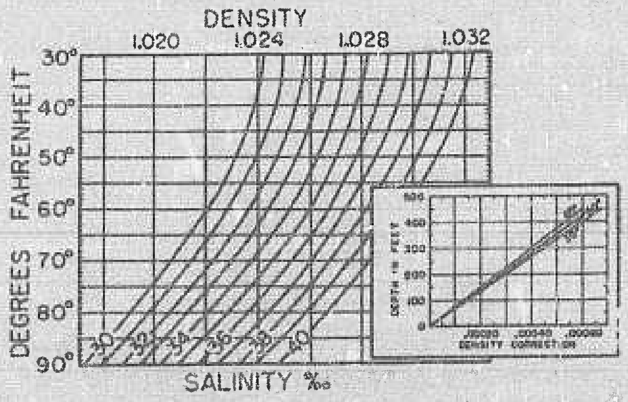


Figure 2. Effect of temperature, salinity, and pressure on density.

surrounding water. Density increases when the salinity or pressure increases, but it decreases when the water expands with increasing temperature. When these properties are known, the density can be determined readily from standard tables such as those of Knudsen.[1] Graphically the relationship can be represented as in Figure 2. It can be seen that the effect of pressure is slight, and it usually can be neglected in oceanographic studies. Temperature and salinity are the factors ordinarily considered, and in most cases temperature is more important.

Water masses of different density tend to arrange themselves in more or less horizontal strata with the lightest water at the surface and the most dense water at the bottom. This is a stable situation since work is required by wind or forces producing turbulence in order to depress the light water or raise the heavier sufficiently to mix them to homogeneity. The effectiveness of the resistance of stable layers to vertical turbulence is indicated by the form of the temperature curve in Figure 1, in which the depth of the mixed layer is a relatively small part of the whole water column.

Continuing the discussion of the simple, three-layered winter ocean, Figure 3 shows a diagrammatic sketch of a north-south profile through the North Atlantic. The relatively warm surface layer is roughly lens-shaped in profile, being deepest in mid-latitudes. The thermocline, too, is deepest and thickest in mid-latitudes, and it intercepts the surface in a narrow band, just beyond the poleward limit of the warm surface layer. In latitudes higher than about 50° the entire water column is relatively cold, and this water is continuous with the cold deep layer that underlies the thermocline further south.

To a certain degree, the distribution of the three primary layers is in agreement with the previous statement that waters of different density tend to form stable horizontal layers. However, it is also evident that the layers do not achieve complete stability, else they would be found at all latitudes from the equator to the poles and with uniform thickness. One of the main reasons for this lack of uniformity is the variation in temperature and amount of solar radiation at different latitudes. In the tropics the water is being heated. As it decreases in density it expands and spreads northward and southward along the sur

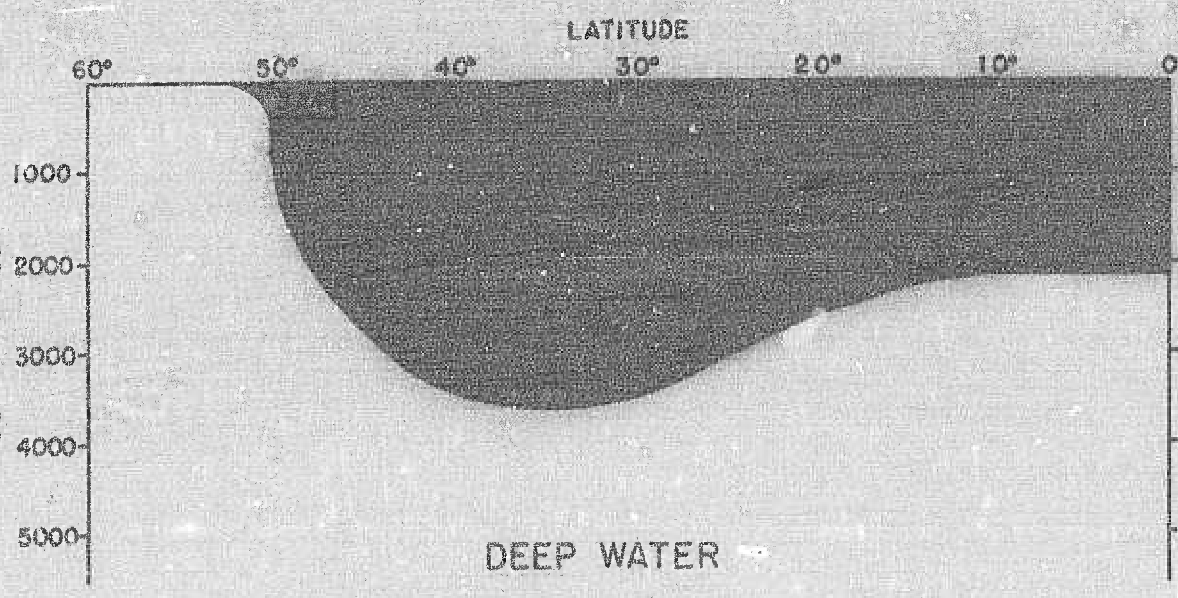


Figure 3. North-south projection of the simple three-layered ocean in winter.

face, gradually cooling as it approaches high latitudes. As the warm surface water is drained off from the tropics it is replaced by underlying cold water that flows in underneath from the polar regions. Thus it is apparent that the deep water layer of all the oceans is ultimately derived from high latitudes and has much the same characteristics of salinity and temperature as the surface waters of those regions.

At a latitude of about 50° North is a zone, pictured diagrammatically in Figure 3, where there is a considerable amount of mixing between arctic water and the warmer water from the south. It is a confused region, hydrographically speaking, with much eddy movement between masses of water of contrasting temperature and salinity, so that sometimes the warmer water near the surface overlies the colder water and sometimes the colder water overlies the warmer water. The surface water carried to this region from the tropics is more saline than the polar water. As it gets colder in high latitudes it becomes dense enough to sink and become part of the main thermocline. At the point of sinking the surrounding surface water converges to take its place. Because of this characteristic, the region around 50° North is called the *subarctic convergence* (a similar zone in the Southern Hemisphere is known as the *subantarctic convergence*). In the thermocline, as in the deep layer, there is a slow drift of water from its point of origin in high latitudes toward the tropics.

The basic vertical temperature structure and the circulation of the ocean have been described as phenomena of heating and cooling and of water movements produced by these changes in density. It will be shown that this basic picture is modified by a number of factors, in particular by the winds, by the earth's rotation, by the configuration of the ocean basins, and by the seasons. These factors will be considered further in the appropriate places. In the meantime, the review of the temperature structure is continued with a summary of practical implications and an examination of some of the temperature observations that have been made.

From the standpoint of subsurface warfare the aforementioned generalizations concerning the distribution of the three primary thermal layers may be roughly summarized as follows:

1. In winter beyond a latitude of about 50° in mid-ocean, and again in mid-latitudes, the water will be virtually isothermal down to the lower limit of submarine operation.

2. The main thermocline approaches the surface in the equatorial region, becoming shallow enough to affect submarine operations by shortening the range on a submarine that is submerged below the isothermal layer. The same is true near the edge of surface currents, such as the Gulf Stream, that transport tropical water to higher latitudes. The thickening of the mixed layer in the central basins of the oceans and the thinning at the periphery are largely the result of the wind systems of the earth, which produce surface currents in the ocean, driving the water in a great eddy in mid-latitudes in each ocean and tending to concentrate the warm surface layer in mid-ocean. The effect of these wind-driven eddies is to improve sound ranges in the middle of the basins and reduce them at the periphery.

3. In the subpolar convergences, where the warm water and the cold water are in close contact, the conditions are variable. Sometimes positive temperature gradients, sometimes negative temperature gradients are encountered.

Following this sketch of the vertical temperature distribution in a somewhat diagrammatic and idealized ocean is a sample of the observations from which this simple picture has been derived. The standard instrument of physical oceanography has been the deep-sea reversing thermometer. Pairs of these instruments are usually lowered in series on a wire cable, the thermometers being attached to a frame known as a *water-bottle*. The mechanism is tripped by a messenger sent down on the cable, which causes the thermometers to turn upside down, breaking the mercury column so that it records the temperature at the depth of reversal. At the same time the bottle closes, securing a sample of water from the same depth. Thus, an oceanographic station, as it is called, consists of pairs of temperature readings, usually at approximately 100-meter (330 feet) depth intervals and a water sample from each depth which is analyzed for salinity and often for various dissolved substances as well.

By using the deep-sea reversing thermometers in pairs it is possible to overcome the difficulty that is caused by the current or the drift of the vessel which ordinarily prevent the wire supporting the instrument from hanging vertically. In each pair of thermometers one is protected by a glass case from the pressure of the water. Because of the compressibility of the glass of the unprotected instrument, it will record a somewhat higher temperature than the pro-

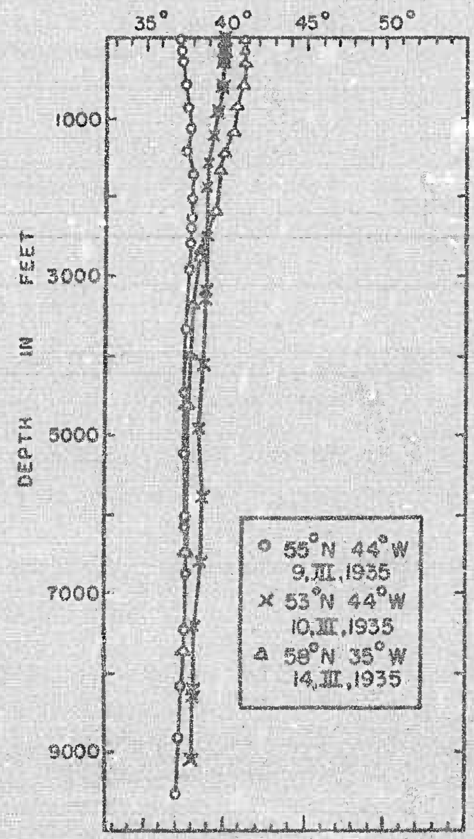


FIGURE 4. Temperature-depth curves for high latitudes in winter.

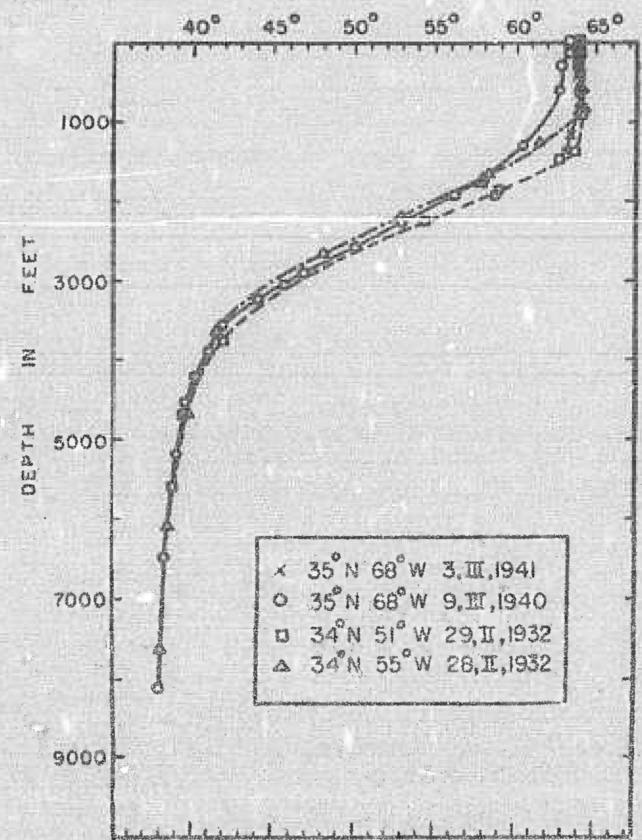


FIGURE 5. Temperature-depth curves for mid-latitudes in winter.

tected instrument with which it is paired. From the differences in reading of the two instruments the depth can be calculated with a very satisfactory degree of accuracy.

When good quality deep-sea reversing thermometers are used at sufficiently close depth intervals and the depths have been corrected for the changing angle of the supporting wire cable, a smooth curve joining the observed points on a temperature-depth plot gives a reliable picture of the major features of the vertical thermal structure at the station in question. Unfortunately, in the past it has not always been possible to use reversing thermometers at sufficiently close depth intervals, especially near the surface.

While the *bathythermograph* [BT] has very obvious advantages, in its standard form it records the temperature down to a depth of only 450 feet. Furthermore, the horizontal distribution of BT observations is as yet inadequate. Therefore, many of the temperature-depth curves given below are primarily based on reversing thermometer observations, but are so drawn as to agree near the surface with the available BT data from the area in question.

5.1.1 High Latitudes

Unfortunately very few data are available from high latitudes in midwinter. Some of these are plotted in Figure 4 and show that the water column is indeed essentially isothermal. Surface temperatures close to 32 F are frequently encountered in the open ocean, and even lower close to the land. But what forms the bottom water in low latitudes is not the coldest water produced each winter near the surface in high latitudes, but the densest. This is water which has a salinity close to 34.8 ‰ and water of such a salinity is not found at the surface over wide areas in winter where the temperature falls to much below 35.6 F.

5.1.2 Mid-latitudes

Many winter stations have been occupied near the centers of the great wind-driven eddies. A selection

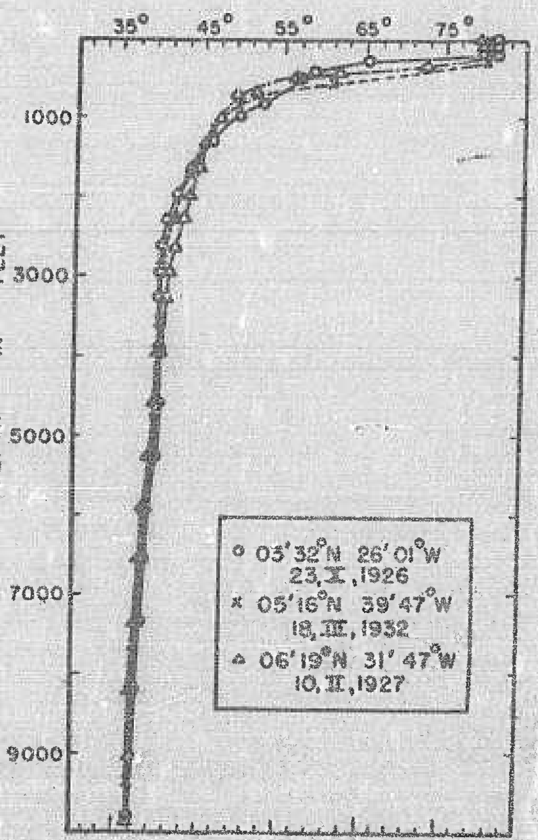


FIGURE 6. Temperature-depth curves for low latitudes in winter.

is shown in Figure 5. It will be seen that the relatively warm, isothermal surface layer extends down to about 1,000 or 1,500 feet. The main thermocline, in which temperature decreases by about 23 F occupies the depths between approximately 1,000 feet and 3,600 feet, while below in the deep water temperature decreases at a fairly uniform rate of about 1 F per 1,000 feet.

5.1.3 Tropics

Figure 6 shows several stations from low latitudes. It will be seen that in the tropics the lower limit of the main thermocline is at about 2,100 feet, some 1,500 feet less than in mid-latitudes and that it extends up to within about 300 feet of the surface. Because of the higher surface temperatures the total temperature drop across the main thermocline is about 15 F greater than in mid-latitudes. The rate of decrease of temperature with depth is also much greater, especially in the upper third of the main thermocline. As pointed out above, because of the small seasonal range in surface temperature in the tropics, summer observations would show much the same temperature-depth distribution.

5.1.4 North-South Temperature-Depth Profile in Mid-Ocean

Unfortunately it is impossible to show the thermal structure of any of the oceans in north-south profile based on midwinter oceanographic stations alone. It is necessary to combine stations made at different seasons of the year and to rely largely on BT data to reconstruct the surface layer. This is justified because below the depth of wind-stirring, seasonal temperature changes are relatively small and result mainly from seasonal changes in the strength of the main currents which only slightly alter the average depth of the main thermocline.

In Figure 7 the available data from the North and

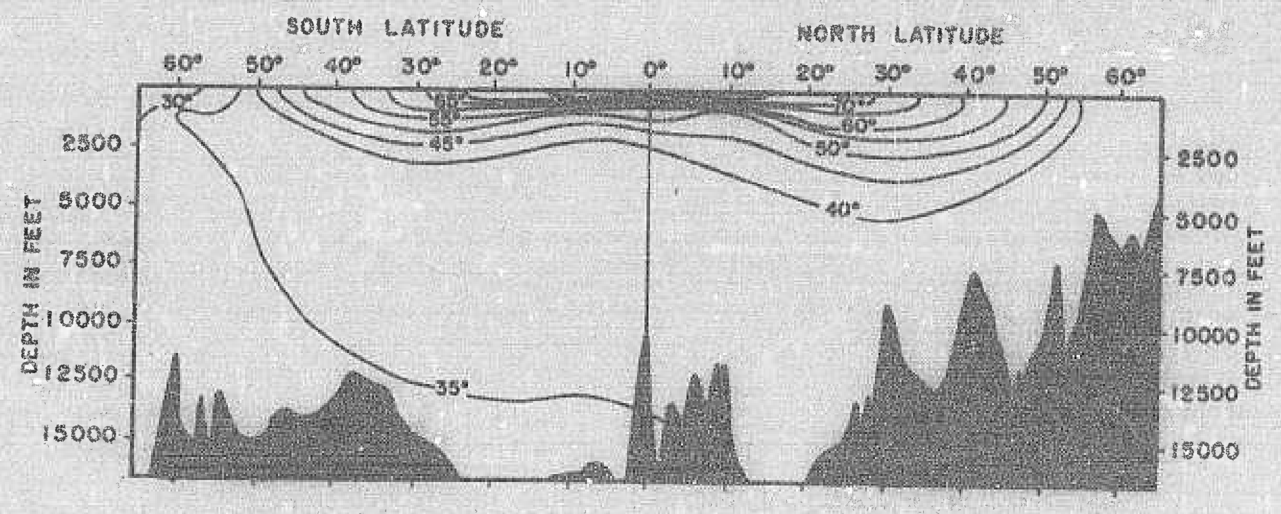


FIGURE 7. North-south temperature-depth profile in mid-Atlantic in winter.

South Alantic have been combined into a mid-ocean profile. In both hemispheres winter conditions are shown. In other words, south of the equator the temperatures near the surface are typical of the July-August period. It will be seen that the Southern Hemisphere half of the section is essentially a mirror image of the northern half and that both are in agreement with the more diagrammatic Figure 3, discussed above.

Such attempts as have been made to construct similar north-south profiles of the other oceans all show the same basic subdivisions: a deep mass of relatively cold water, having but a slight and nearly uniform decrease of temperature with depth; a main thermocline at mid-depths, except in high latitudes; and above the main thermocline in winter a layer of relatively warm water of varying thickness in which there is virtually no temperature change with depth.

3.1.5 Geographical Variations of the Primary Layers

Because of the difficulty of representing the ocean in a three-dimensional diagram, it is necessary to resort to indirect methods in order to picture the horizontal and vertical dimensions of the three primary layers.

The difference between the minimum (winter) surface temperature and the temperature at a depth of 600 feet is shown in Figure 8. In equatorial regions the top of the main thermocline extends well above the 600-foot level, so that the temperature difference between the surface and this depth is relatively large. Northward and southward the difference becomes much less as the surface layer thickens and the thermocline comes to lie at a greater depth. Beyond the poleward limits of the main thermocline there is little temperature change with depth. Hence the zero line marks off approximately the limits of the main thermocline and the position of the subpolar convergences previously mentioned.

Some idea of the geographical variations of the warm surface layer can also be obtained from the layer depth on the sonar charts. These are reproduced in Figure 9, which shows the average layer depth during December, January, and February, and in Figure 10 which is for June, July, and August. A precise definition of layer depth is difficult, but it is usually the depth to the most prominent break in the temperature-depth curve. This is commonly at the top of the seasonal thermocline, if present; otherwise, at the top of the main thermocline. The charts for the winter season (Figure 9, Northern Hemisphere; Figure 10, Southern) show the geographical details of some of the features that have already been mentioned: a mixed layer of 300 feet or more in each of the central basins in mid-latitudes, a shallower layer toward the continents on each side and toward the equator. However, as there is no marked change in layer depth in the region of the subpolar convergences, the sonar charts show little evidence of this phenomenon.

In the part of the charts depicting the summer season layer depths are, of course, shallower because of seasonal warming of the surface waters, and the charts no longer show the position of the main thermocline. Discussion of this part of the charts is postponed until the seasonal temperature cycle has been described.

The lower part of the main thermocline and the underlying deep water are of less interest from the practical standpoint than the surface layer. However, in a few places they come close enough to the surface so that a submarine can operate in them. As was shown in previous figures, there is a gradual change in the slope of the temperature-depth curve between the middle of the main thermocline and the deep water. At no place is there a sharp break where the one ends and the other begins. But for practical purposes the lower limit of the main thermocline can be set at a temperature of about 41 F, below which further decreases in temperature with depth are very slight.

In equatorial regions the depth of the 41-degree isotherm is generally about 2,000 feet, although in a few areas it is much shallower. Along the west coasts of the continents, currents set up by the trade winds transport surface water away from the land, thinning out the warm surface layer so that the thermocline and deep water layer are drawn up near the surface. This process is known as *upwelling*, and where it occurs to a pronounced degree, the 41-degree isotherm may rise to within 300 feet of the surface.

To the north and south of the equator the 41-degree isotherm slopes downward, reaching its greatest depths, 3,600 to 4,000 feet, in the central basins in mid-latitudes. It shoals toward the periphery of the wind-driven eddies and comes to the surface in higher latitudes in the subpolar convergences.

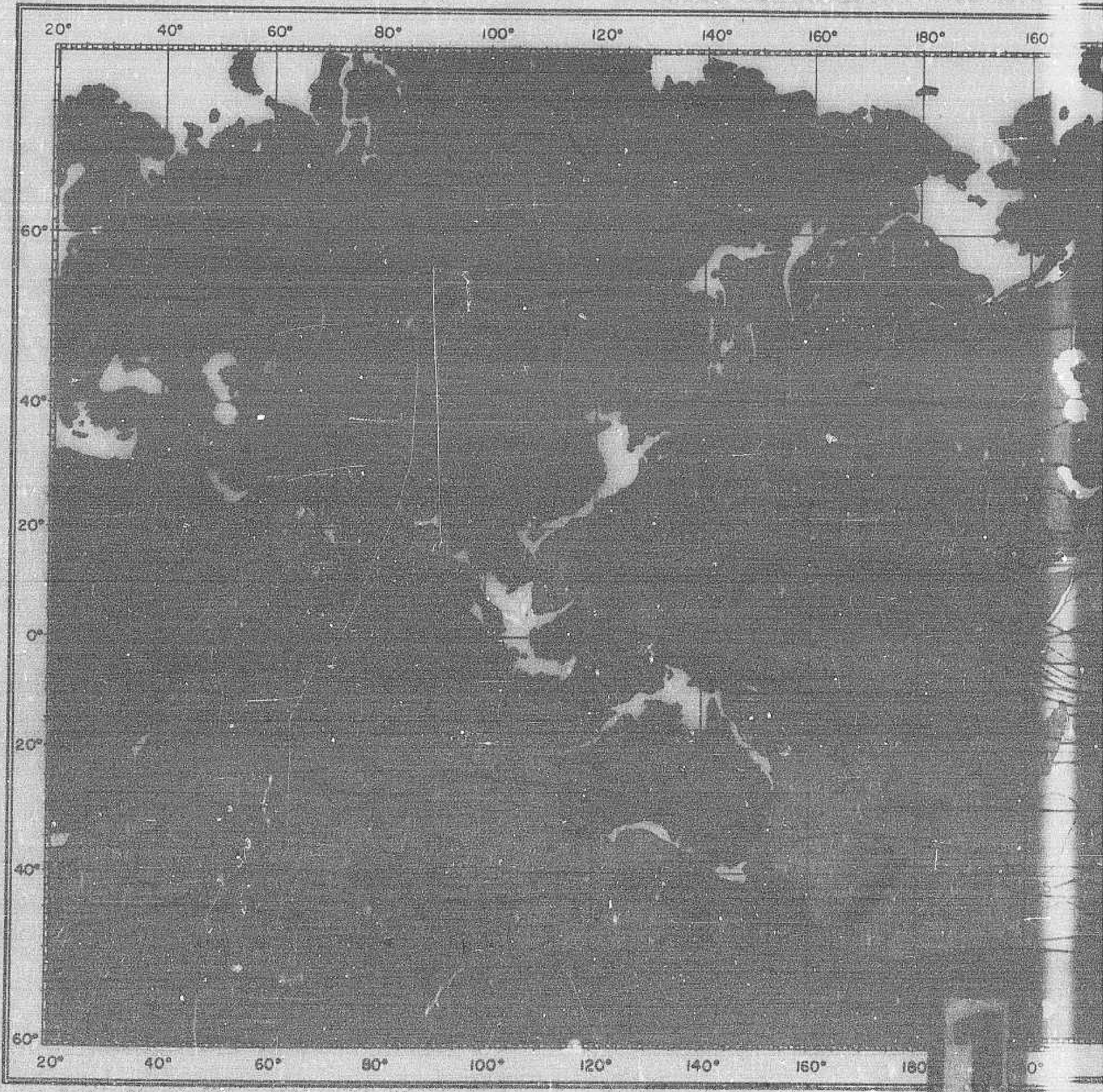


FIGURE 8. World chart show

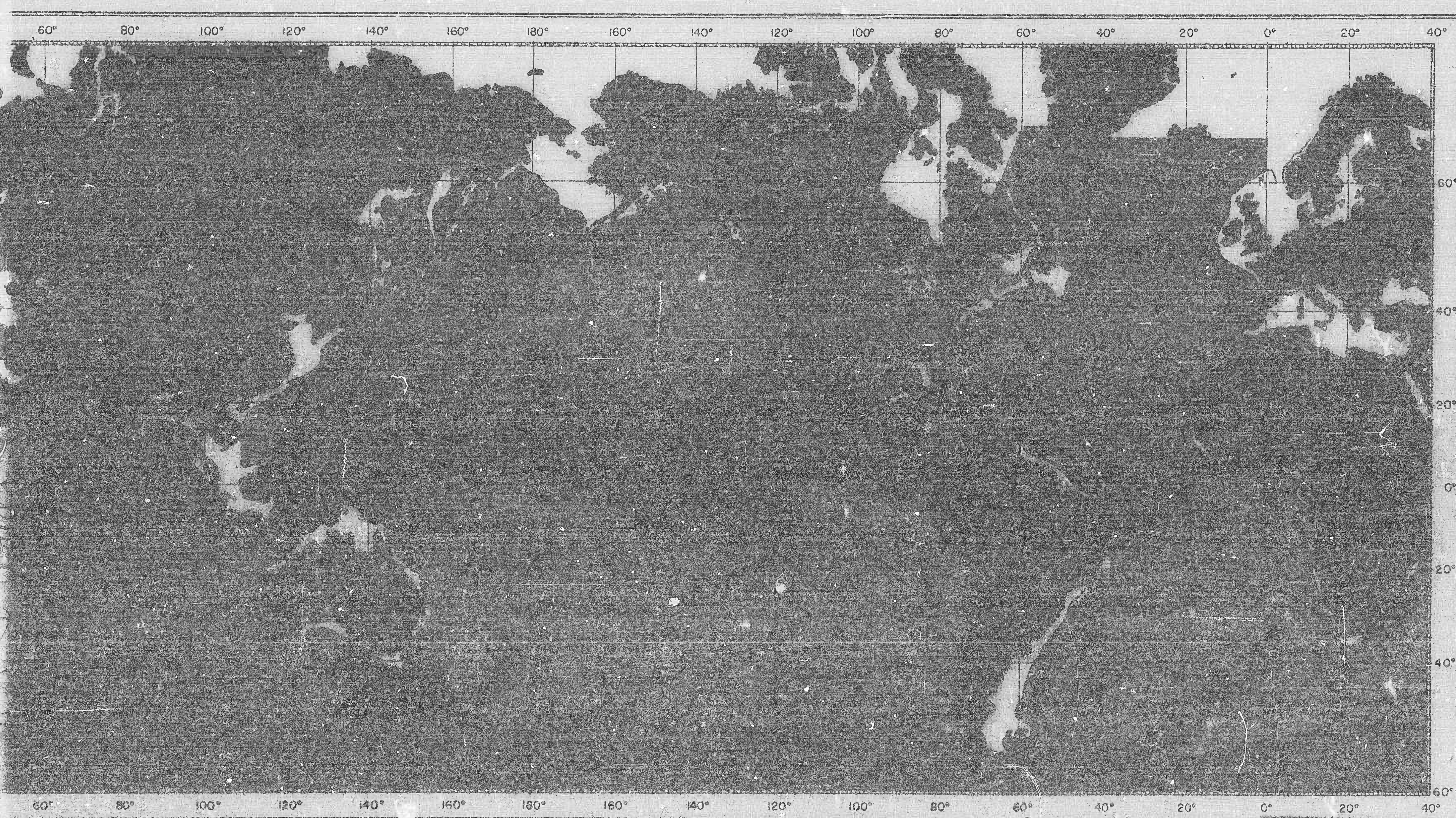


FIGURE 8. World chart showing minimum temperature at the surface minus the temperature at 600 feet.

FIGURE 9. World chart showing average layer depth during December, January, and February.

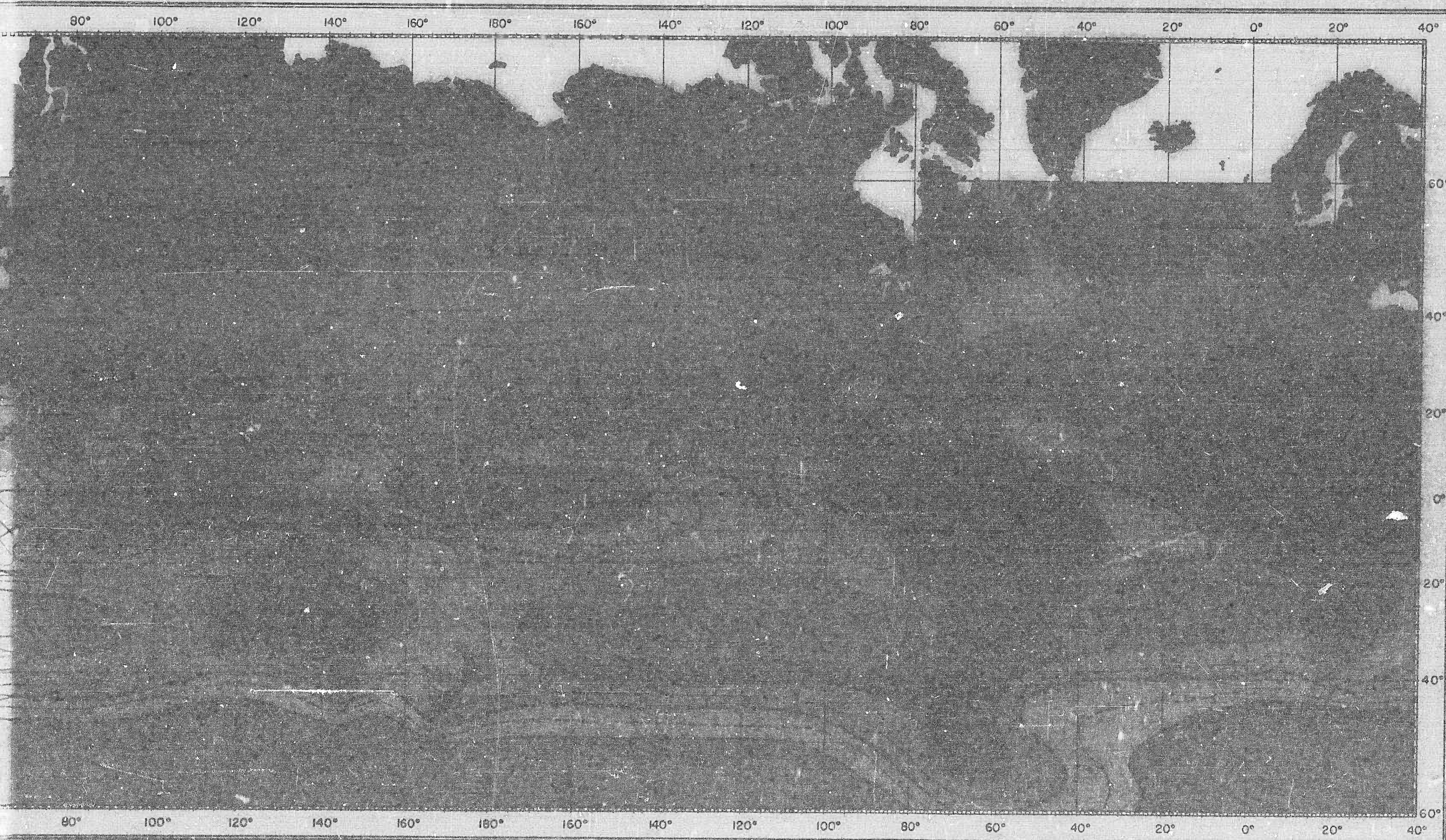


FIGURE 9. World chart showing average layer depth during December, January, and February.

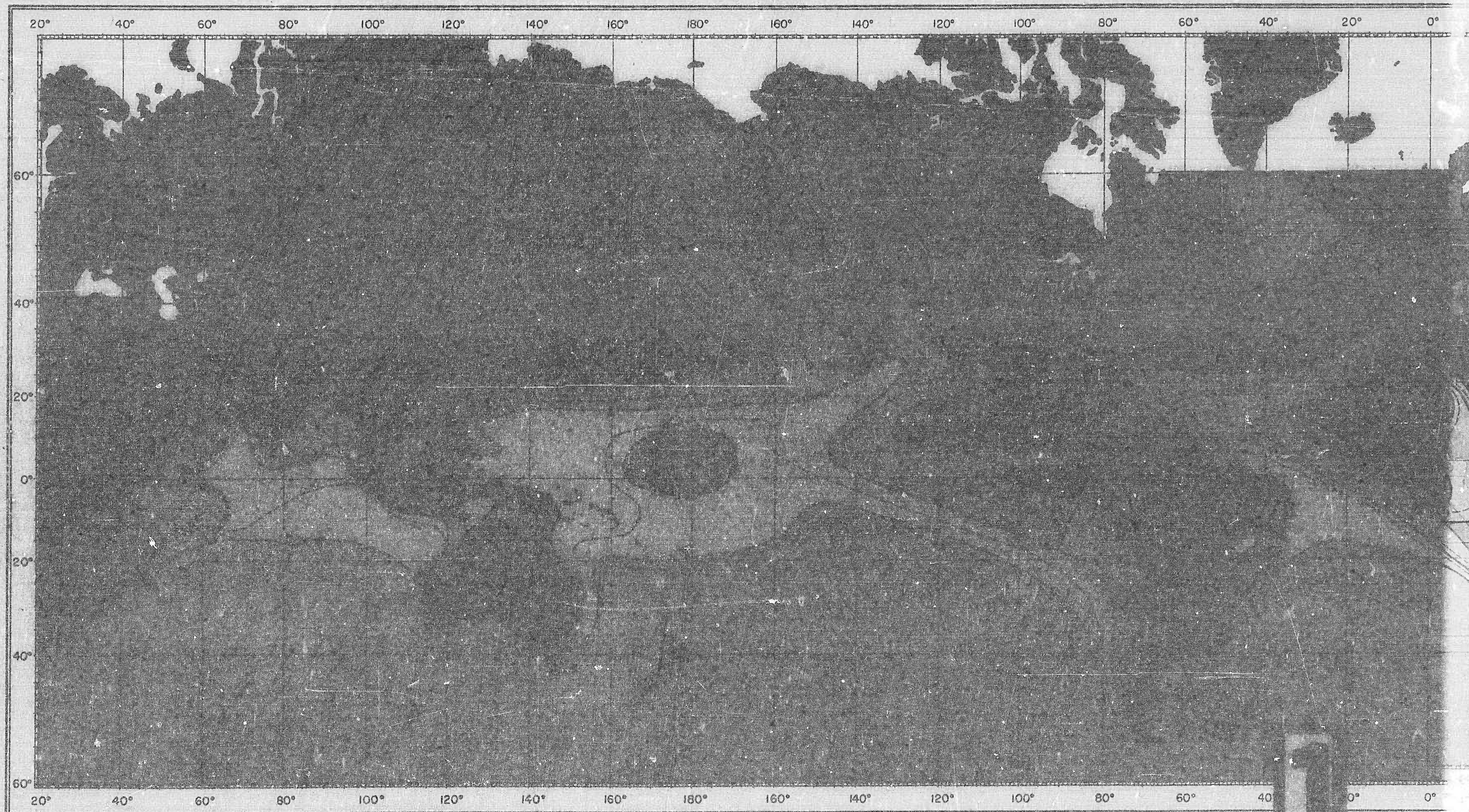


FIGURE 10. World chart showing average layer depth during June, July, and August.

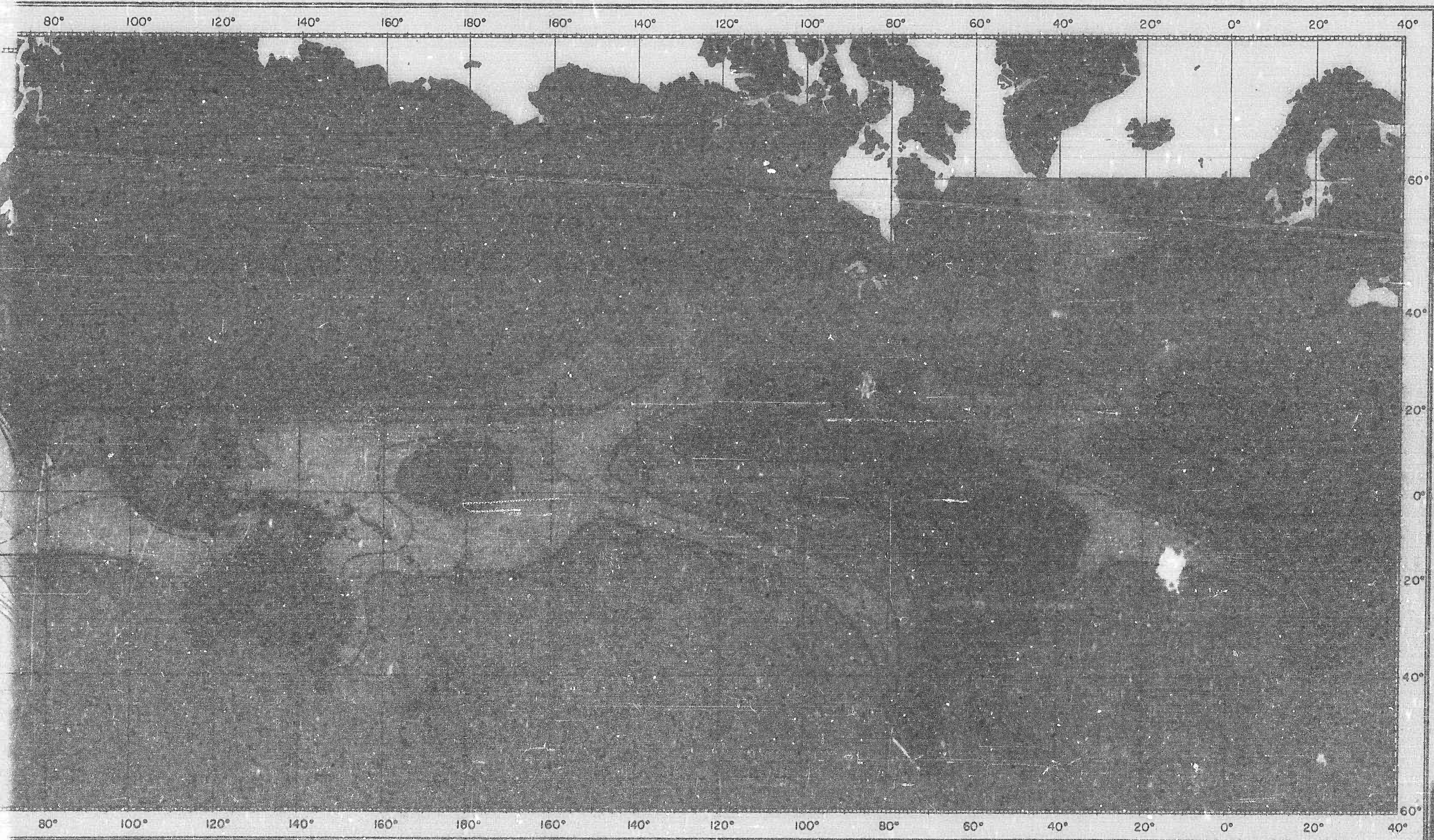


FIGURE 10. World chart showing average layer depth during June, July, and August.

RESTRICTED

2

5.2 DIURNAL AND SEASONAL CHANGES

5.2.1 Heat Exchange at the Sea Surface

Since the temperature of the earth as a whole is not changing appreciably, it is clear that the total amount of heat received from the sun must exactly equal the amount lost by radiation back into space. But though the total heat budget must always balance, the solar radiation and the loss of heat by radiation from the surface (called back radiation) at any one place and time seldom do. At any given place and time the surface of the planet is either warming or cooling. Local variations notwithstanding, the intensity of solar radiation is largely a function of latitude and season, and the difference in temperature between the tropics and the poles would be much greater than it is if it were not for the relatively free circulation of the atmosphere and the oceans. This causes the large-scale transfer of water mentioned earlier, and locally it gives rise to convection currents and largely controls the immediate details of the surface layer.

Since the surface of the sea is an interface between air and water, the heat exchange involves other factors besides radiation. Conduction may be in either direction depending on whether air or water is warmer. Evaporation (and its opposite, condensation) and precipitation affect not only temperature but salinity as well, and so influence the density of the water in two ways. In the case of evaporation, the two factors always work together; evaporation makes the water denser both by cooling it and by increasing its salinity. Precipitation, on the other hand, always makes the water fresher, and so tends to make it less dense, but it may either warm or cool it according to the temperature of the rain. Figure 11 shows a bathythermogram taken a few hours after a heavy rain. Here the rain was evidently colder than the sea and there is a strong positive temperature gradient between the layer of cool, fresh, rain-diluted water and the warm, salty water underneath.

Of the processes just mentioned all but solar radiation influence directly only the surface film. In the absence of mixing, only conduction and diffusion, which are relatively ineffective, can carry downward the changed surface conditions. Solar radiation, however, has some power of penetration. The depth of penetration varies with the wave length of the radiation, being greatest in the visible part of the spectrum and much less for infrared and ultraviolet rays. In general, for any water of uniform transparency the rate of absorption for any particular wave length will be constant; that is, if a certain per cent of the entire amount of energy of that wave length is absorbed in the first inch of depth, the same per cent of the remaining energy will be absorbed in the second inch, and so on. This characteristic is illustrated in Figure 12, in which the percentage of light penetration is plotted on a logarithmic scale against depth. The fact that the data for each kind of water follow very nearly a straight line is indicative of a constant rate of absorption. Light penetration depends to a large degree on the transparency of the water. Pure water is highly transparent, but the sea is more or less turbid; it contains opaque particles in suspension that absorb almost all the radiation that strikes them. Hence Figure 12 shows a greater depth of light penetration in the clear waters of the central Atlantic than in the more turbid coastal waters.

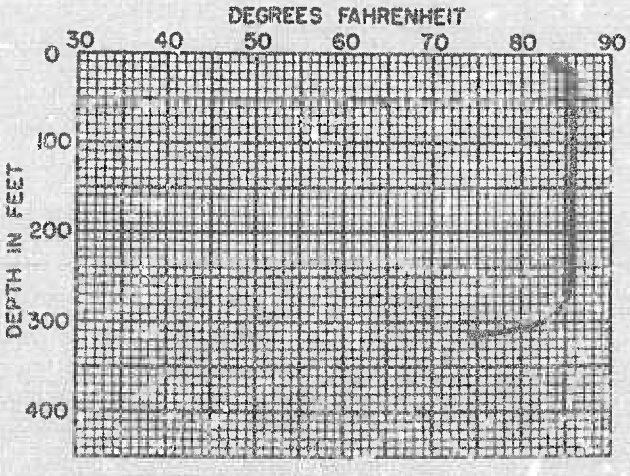


FIGURE 11. Bathythermogram showing positive temperature gradient at the surface due to rain.

Since heat is produced when radiant energy is absorbed, the data on light absorption give an idea of the general characteristics of surface heating. However, it is important to note that by far the most significant part of surface heating is accomplished not by visible light but by infrared radiation, which has less power of penetration and a much higher absorption rate. Thus, if absorption curves for infrared radiation were shown in Figure 12 (which is for visible light only) they would be much more nearly horizontal, and would cross, say, the 50 per cent line only a few feet below the surface even in the clearest water. Further, it is obvious that the absorption curve

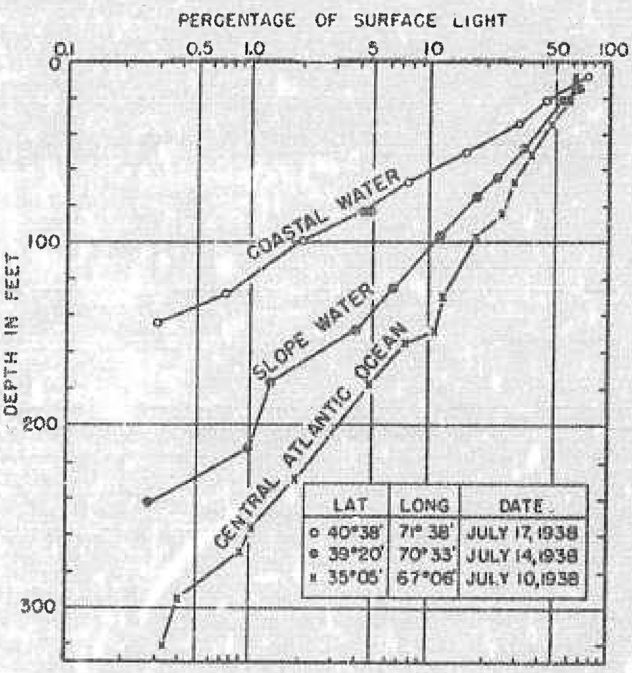


FIGURE 12. Absorption of visible light by sea water.

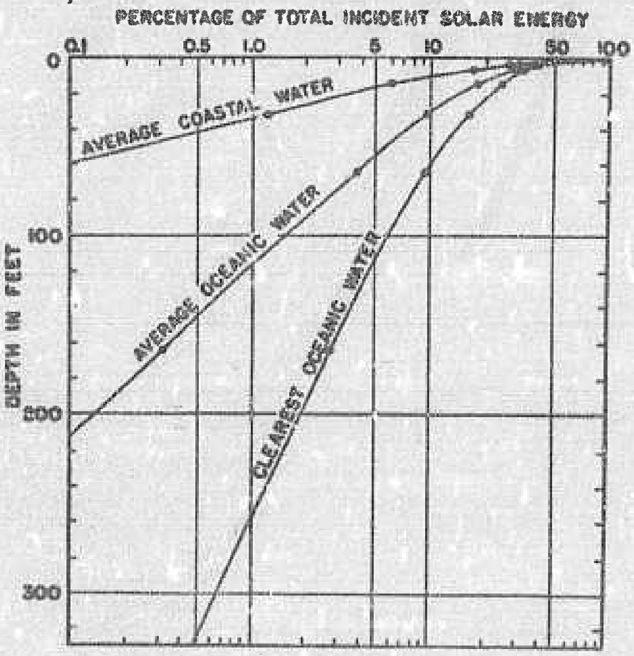


FIGURE 13 Absorption by sea water of total incident solar energy.

for total incident solar energy will not be linear, since it combines all wave lengths present. Figure 13 shows the absorption of total solar energy as computed for several different kinds of ocean water. In the absence of convection or turbulent mixing the temperature gradient produced by solar heating can be expected approximately to follow such an absorption curve. The heating will be greatest at the surface and will decrease rapidly with depth. The maximum depth at which a measurable increase in water temperature occurs will be perhaps 10 to 30 feet.

This situation is nearly always modified by vertical mixing which tends to distribute the heated surface water downward. Thus the observed temperature increase at the surface is less than would be predicted according to radiation measurements, and the increase at lower depths is greater. Indeed in 70 or 80 per cent of the observations that have been made, vertical mixing has been sufficient to distribute heat completely uniformly, so that there is no observable temperature gradient.

Diurnal Warming

The daily variation in the temperature of the superficial layer of water that occurs as a result of heating during the day and cooling at night is known as diurnal warming. An example of the kind of diurnal warming that occurs during calm weather is shown by the series of bathythermograms in Figure 14. In the early morning the temperature of the water was essentially uniform. During the middle of the morning surface heating became strong enough to create a slight negative gradient in the upper few feet. Heating progressed during the day, and the negative gradient reached its maximum development in the late afternoon. Then cooling processes and vertical mixing gained the upper hand, producing a shallow mixed layer which apparently deepened during the night until the negative gradient was destroyed. Early the following morning the water column was again essentially isothermal except for a slight positive temperature gradient at the surface. The latter occasionally happens when surface cooling is pronounced and the weather is calm.

Figure 15 shows a similar series of bathythermograms taken during a 2-day period. The general features of diurnal warming are similar to those previously shown, but the figure serves to illustrate minor variations in the form of the negative gradient and the depth of heating such as are commonly encountered.

Sometimes during very calm weather the negative gradient formed during the daytime is not completely destroyed at night. Then the next day's surface heating is superimposed on the residual gradient from the previous day. Figure 16 shows an example

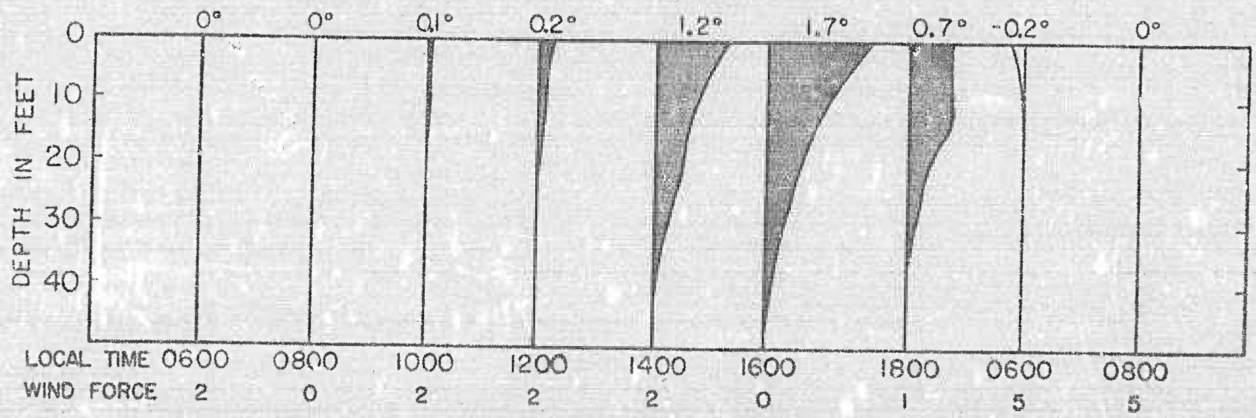


FIGURE 14. Bathythermograms illustrating diurnal warming.

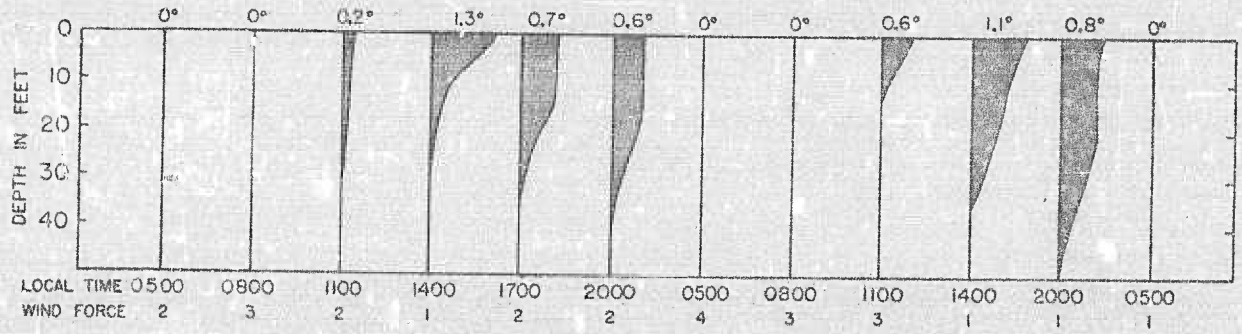


FIGURE 15. Bathythermograms illustrating diurnal warming.

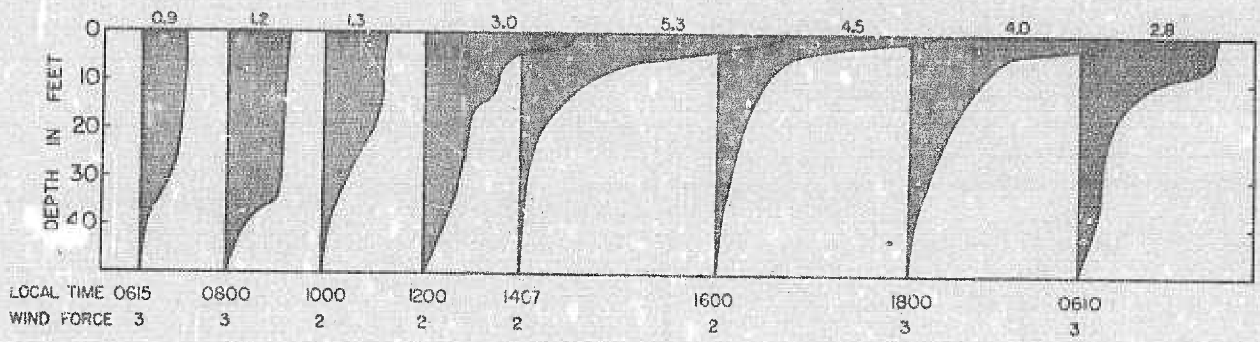


FIGURE 16. Bathythermograms illustrating diurnal warming.

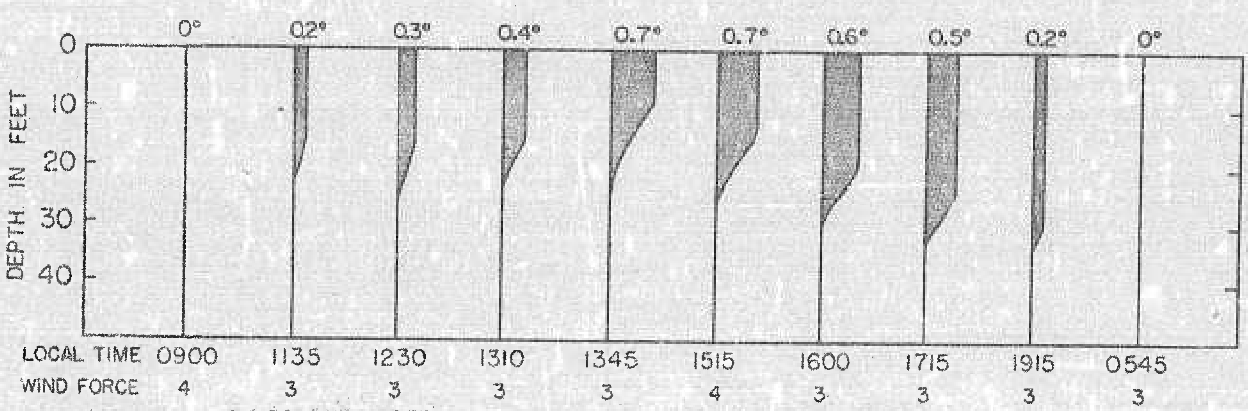


FIGURE 17. Bathythermograms illustrating diurnal warming.

of the very strong temperature gradients that can result from such a situation. Vertical mixing is reduced to a minimum, partly because of calm weather, and also because turbulence decreases with increasing stability. These temperature curves therefore approximate very closely the theoretical curve for the penetration of solar radiation.

By contrast, Figure 17 shows a series of bathythermograms taken on a day when there was a gentle to moderate breeze which maintained a shallow mixed layer separated from the main body of isothermal water below by a small thermocline. With still stronger winds the mixed layer would extend deeper, and generally when the wind force is 4 (Beaufort) or more, the downward distribution of heat takes place rapidly enough to prevent the formation of shallow negative gradients.

Small amounts of diurnal warming occur frequently with little or no effect on sonar performance. However, the establishment of negative gradients at or slightly below projector level can cause marked reduction of echo ranges. The amount that the range is reduced depends not only on the total decrease in temperature in the water above target depth, but also on the form of the temperature-depth curve. In general, however, a temperature difference of 0.4 F or more between the surface and 30 feet will seriously reduce the range, and this has been chosen as a definitive value in the Navy manuals.

From the standpoint of subsurface warfare it is important to know under what conditions range reduction can be expected. Since diurnal warming is most pronounced in the afternoon, it is expected that range reduction will be most frequent at that time. This is illustrated in Figure 18, which shows the percentage of periscope depth ranges less than 1,500 yards determined by the prediction rules used for the Sonar Charts. According to these rules, a temperature decrease of about 0.4 Fahrenheit in the top 30 feet of the ocean reduces the periscope-depth range to less than 1,500 yards. To compute the data required for Figure 18, all the available bathythermograms have been used for eight oceanic areas, whose positions are charted in Figure 19. The maximum frequency of short ranges occurs at about 1600 local time in all the areas, and the minimum frequency is at night. There are also geographic variations in the frequency distributions, short ranges being more common in coastal waters than in deep oceanic areas in the same latitude, and more common in high and mid-latitudes than in low. The frequency of range reduction is also greater in summer than in winter, and the difference is more pronounced in the higher latitudes, where there is a well-defined seasonal climatic cycle, than in the tropics where the weather is more uniform throughout the year.

A complete analysis of diurnal heating would require consideration of all the processes of heating and cooling at the sea surface. The variability of these processes depends on local weather and climatic

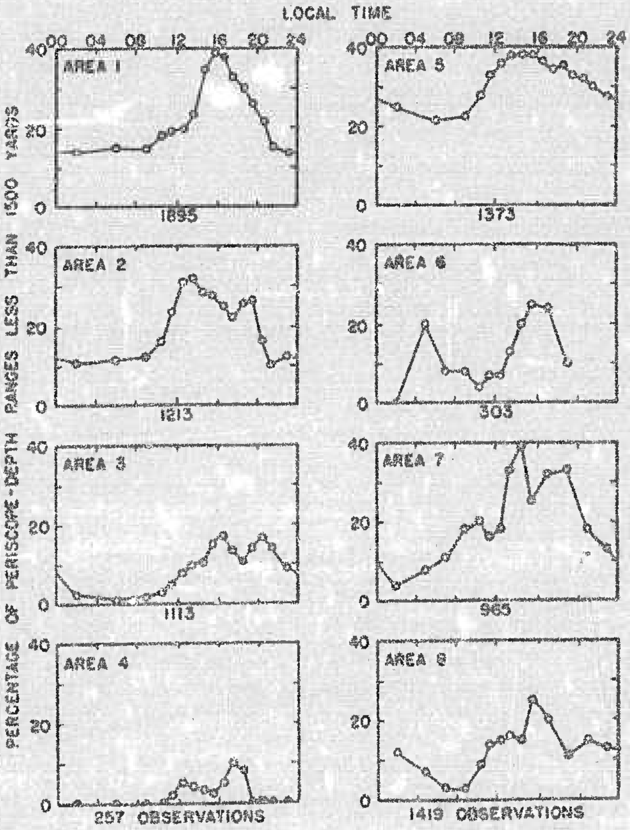


FIGURE 18. Diurnal frequency of reduced ranges in various areas.

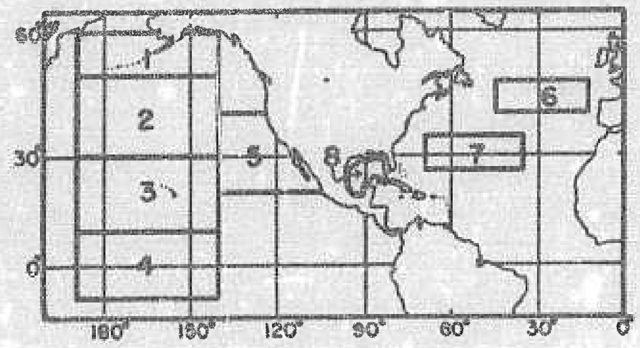


FIGURE 19. Positions of areas used in Figure 18.

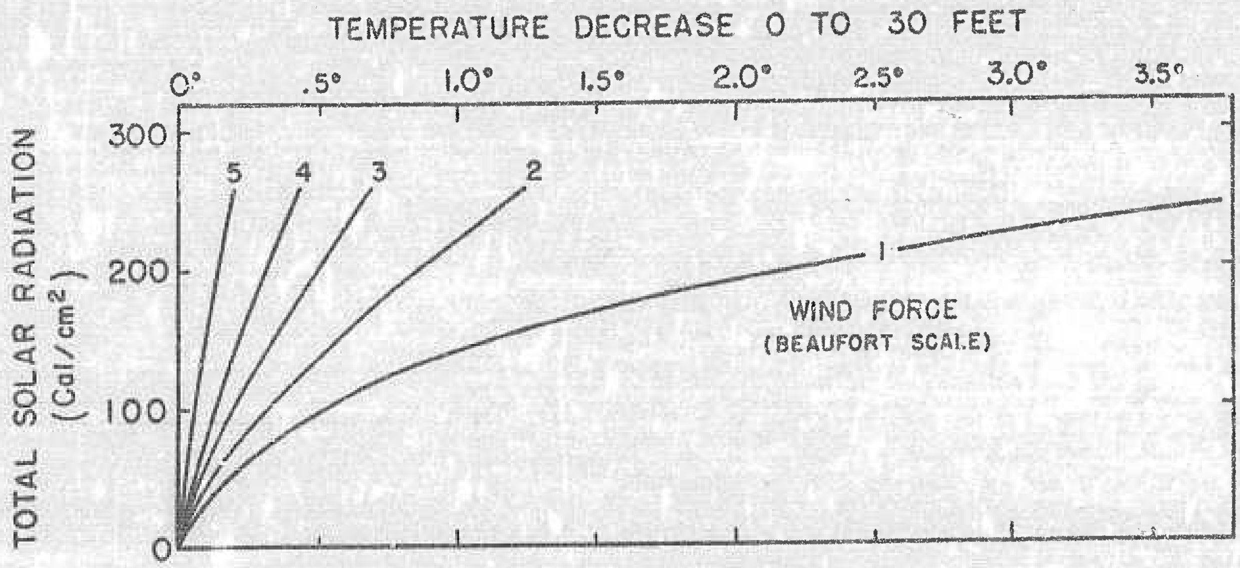


FIGURE 20. Effect of wind on diurnal warming.

factors; hence these factors can be used to predict diurnal heating. The variables which appear to be most significant are the noon altitude of the sun, wind force, the degree of cloud coverage, the difference in temperature between air and water, and the humidity of the air.

In the spring of 1942 a 25-day study[2] of solar heating was made in the Gulf of Mexico. Hourly BT lowerings were made during all this period and detailed meteorological records were kept. The principal conclusions drawn from these data can be summarized as follows:

1. During spring in the Gulf of Mexico the effect of the wind on the downward penetration of heat can be plotted as in Figure 20. This diagram shows the negative temperature difference to be expected as the wind strength and the heat balance vary.

2. At the time these observations were being carried out, a negative gradient of 0.3 degree was considered critical. To produce such a gradient with a force 4 wind the excess incoming heat, between the hours of 0800 and 1100, must exceed 200 calories per square centimeter. With a force 3 wind the minimum heat value is 140 and with a force 2 wind it is 100.

3. On no day was the residual heat sufficient to produce the critical temperature gradient with a force 5 wind.

4. The heat balance can be calculated from hourly meteorological observations made during the morning, or it can be estimated with somewhat less accuracy from such a nomogram as shown in Figure 21, using the average cloud coverage and the average difference in temperature between the air and the water during the morning.

5. On only two days did the morning observations fail to forecast the afternoon temperature gradients as well as could be known by computing the heat balance for the whole day. On these exceptional days

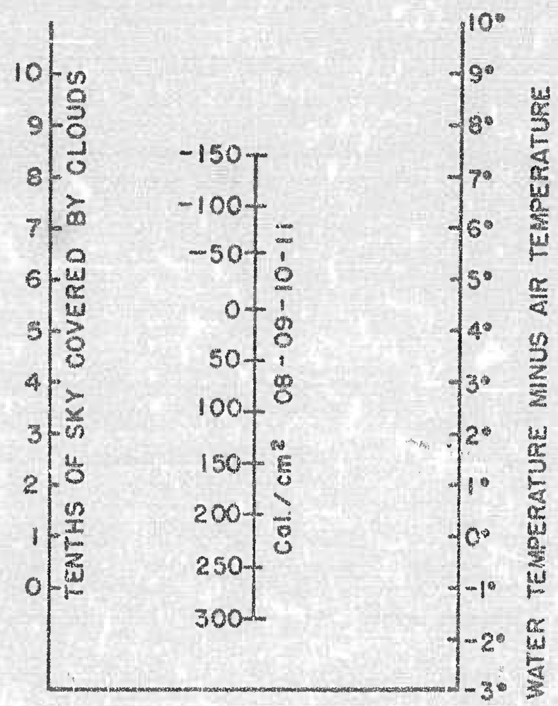


FIGURE 21. Nomogram for determining heat balance in the Gulf of Mexico.

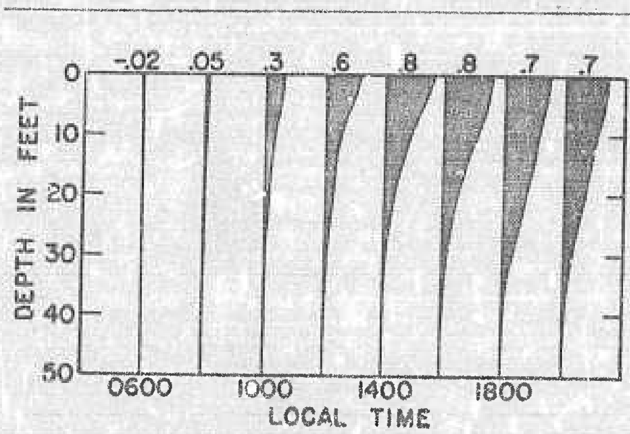


FIGURE 22. Temperature-depth curves from a Pacific weather station illustrating diurnal warming.

overcast skies in the morning changed to clear in the afternoon.

Similar series of bathythermograms have been taken at a weather patrol station in the northeastern Pacific (40°N, 150°W). They serve to show several additional characteristics of diurnal warming which should be included in the present discussion. Twenty-four daily series of bathythermograms were analyzed. Each series consisted of observations covering the period from 0600 to 2000 local time, plus at least one from the following morning. In each case the first observations showed either completely isothermal water or isothermal water underlying a slight positive gradient. Then there developed at the surface a negative gradient which sometimes reached a depth of nearly 50 feet. By the following morning this had completely disappeared and the water was once more isothermal or slightly cooler at the surface. For each series the temperature was measured at 5-foot depth intervals and plotted in Figure 22 as the average difference between the temperature at each depth and the temperature at 50 feet. Thus an average picture is obtained of the amount of heating and cooling over a period of several days.

Figure 23 presents the same measurements in a different way. Here the average increase in temperature above that at the 50-foot depth is plotted against time, for each 5-foot level. This makes it possible to compare easily the amount and rate of temperature increase at different depths. The figure shows that the greater the depth, the later the hour when the water reaches its maximum temperature. This is because at any considerable distance below the surface the gain in heat is not so much from absorption of radiant energy as from downward conduction by vertical eddy motion, which takes place increasingly slowly at greater depths and causes a progressive lag in the rate of heating.

Thus far the discussion has largely centered around the simplest cases of diurnal warming, in which the negative gradient represents the effects of 1 day's heating. From the practical standpoint, however, it is important to consider all cases of surface

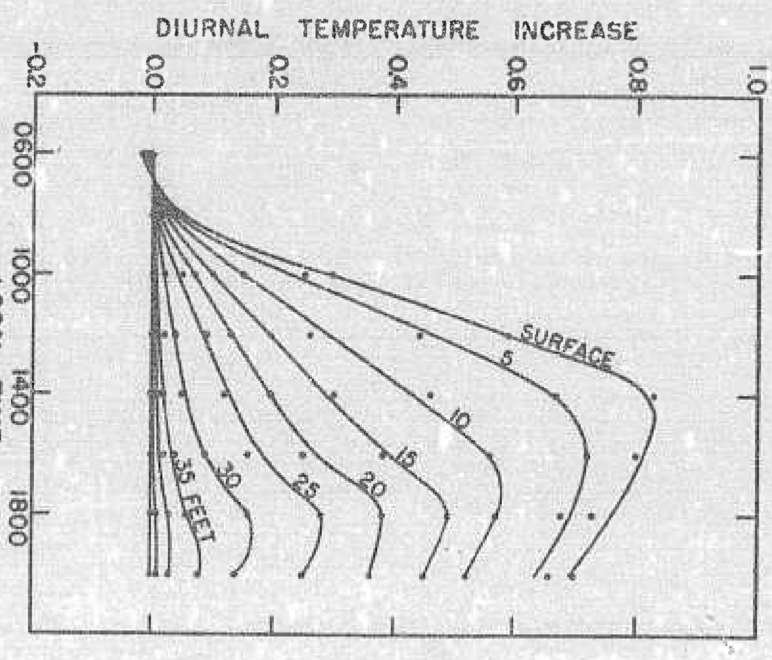


FIGURE 23. Diurnal temperature change at various depths from the surface to 50 feet.

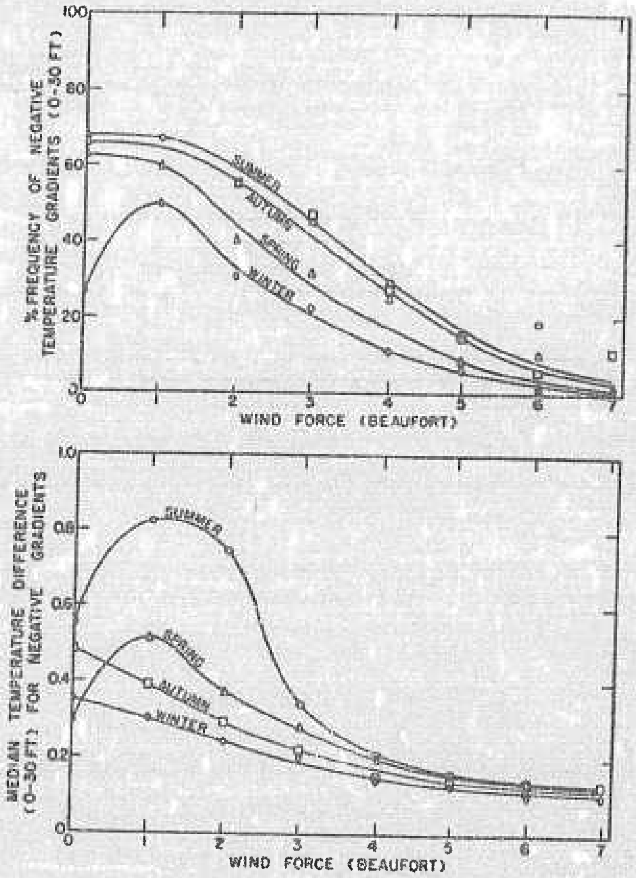


FIGURE 24. Relationship between shallow temperature gradients and wind at different seasons.

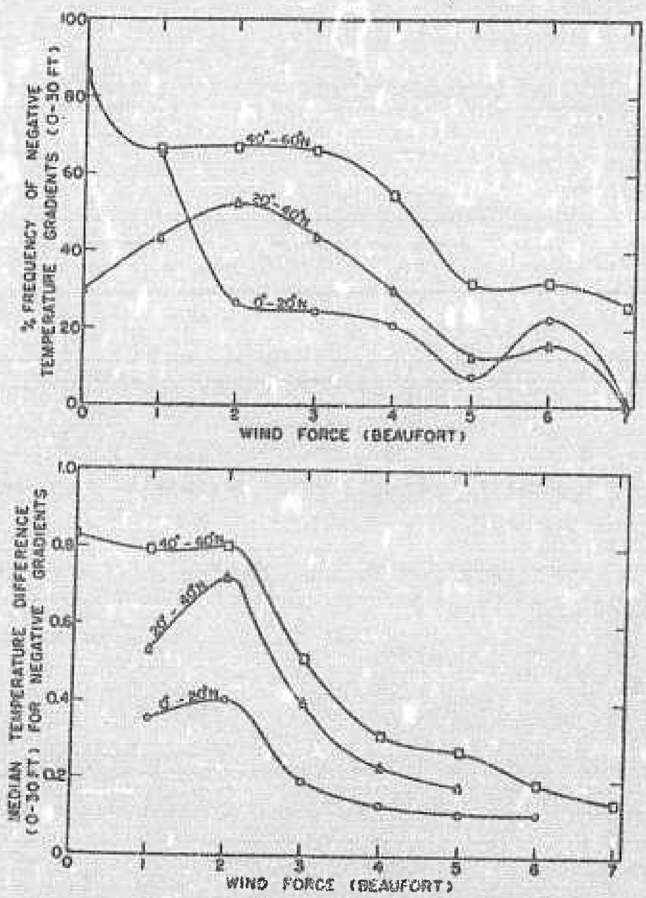


FIGURE 25. Relationship between shallow temperature gradients and wind at different latitudes during the summer season (June, July, and August).

negative gradients, both the simple ones and those in which a period of calm weather has permitted the accumulation of a negative gradient for several days. For this purpose a large group of BT observations from the Pacific have been examined from the standpoint of the weather conditions at the time the observations were made.

In Figure 24, the upper graph shows the frequency of negative gradients for different wind forces for each season of the year. Any measurable decrease in temperature between the surface and a depth of 30 feet was called a negative gradient. In the lower graph are plotted the median values of those temperature differences which were not zero; if the isothermal cases had been included, a majority of the median values would, of course, have been zero. Thus, the two parts of Figure 24 must be considered together: the upper part shows how often measurable negative gradients occur; the lower, their relative strength when they do occur. In general, Figure 24 shows the greater frequency of negative gradients during the warmer part of the year, and it also suggests that seasonal changes affect the magnitude of the gradients more than they affect the frequency of their occurrence. A possible weakness of the figure is that it combines data from a wide range of latitude. Perhaps most of the winter observations showing negative gradients came from relatively low latitudes. It is to be hoped that as bathythermograms become more numerous the various factors influencing the formation and persistence of temperature gradients may be more clearly separated.

Figure 25 shows the effect of wind on surface heating at different latitudes during the summer season. In the wintertime the difference between high latitudes and low latitudes is undoubtedly much less, if not actually reversed.

Both Figures 24 and 25 are in general agreement with previous statements that wind-generated vertical turbulence is destructive to surface temperature gradients. But whereas in the previous discussion it was stated that diurnal heating does not develop

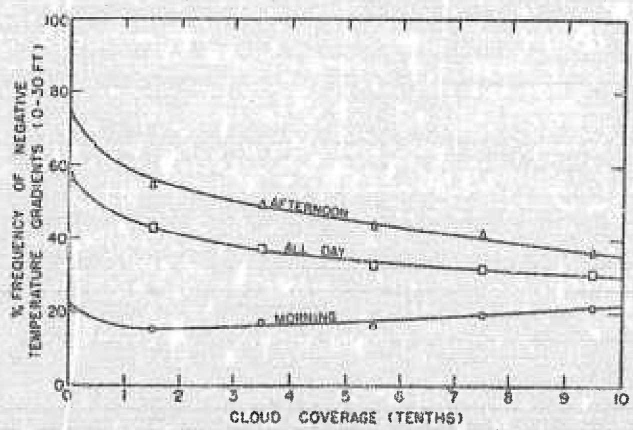


FIGURE 26. Relationship between shallow temperature gradients and cloud coverage.

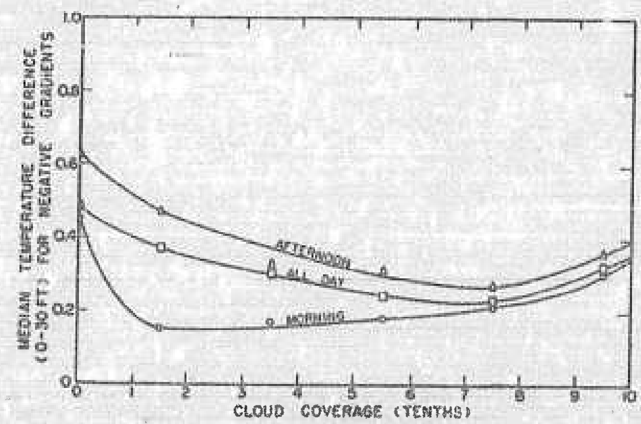


FIGURE 27. Relationship between shallow temperature gradients and cloud coverage.

when the wind is much more than force 3 (Beaufort), here it is apparent that a small but significant number of negative gradients are found when the wind force is 5, 6, or even 7. The difference lies in the fact that any average set of observations will contain a number of cases in which a strong negative gradient is built up during several days of calm weather. Then the stability so obtained requires a much stronger wind to destroy the gradient than would have been needed to prevent its formation in the first place.

The Pacific observations have also been correlated with cloud coverage. The usual method of evaluating clouds by estimating the per cent of sky covered is by no means an accurate measurement of the extent to which clouds reduce solar radiation. Nevertheless, Figures 26 and 27 show a significant relationship between the amount of clouds and suppression of surface heating except in the morning observations. In this case it seems likely that during the hours of the day when back radiation exceeds insolation, clouds may sometimes serve as a blanket holding in the surface water's heat.

The effect on diurnal warming of the difference between air and sea temperatures has not yet been analyzed thoroughly except in the small group of Gulf of Mexico observations previously referred to. There it proved to be one of the more important factors. Moreover, the available data on the geographical distribution of air-sea temperature difference (Figure 28) indicate that areas where this difference is largest coincide with regions of pronounced diurnal warming.

The whole problem of surface heating is complicated by the fact that the various processes are so closely interrelated. The quantitative relationships cannot be solved without a great deal more scientific work on the processes involved and statistical examination of the observations. However, it is not too much to expect that eventually echo ranges will be predicted in much the same way that weather forecasts are made.

CONVECTION

Convection has been mentioned frequently in connection with heat exchange at the surface. It has been

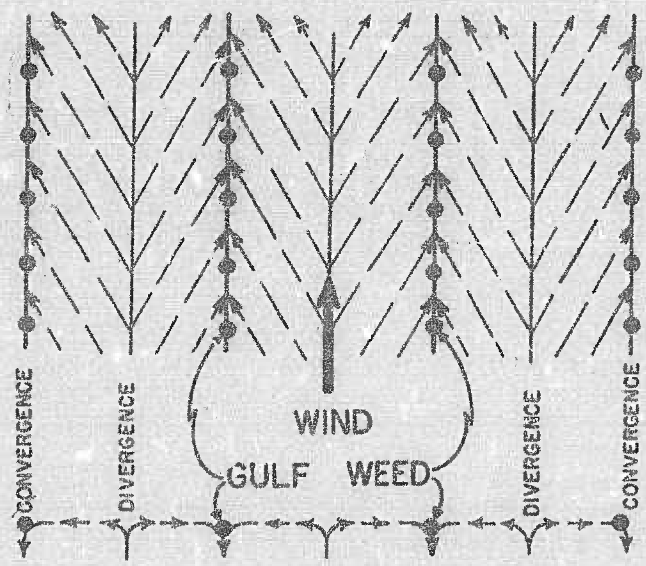


FIGURE 29. Diagrammatic representation of convection cells.

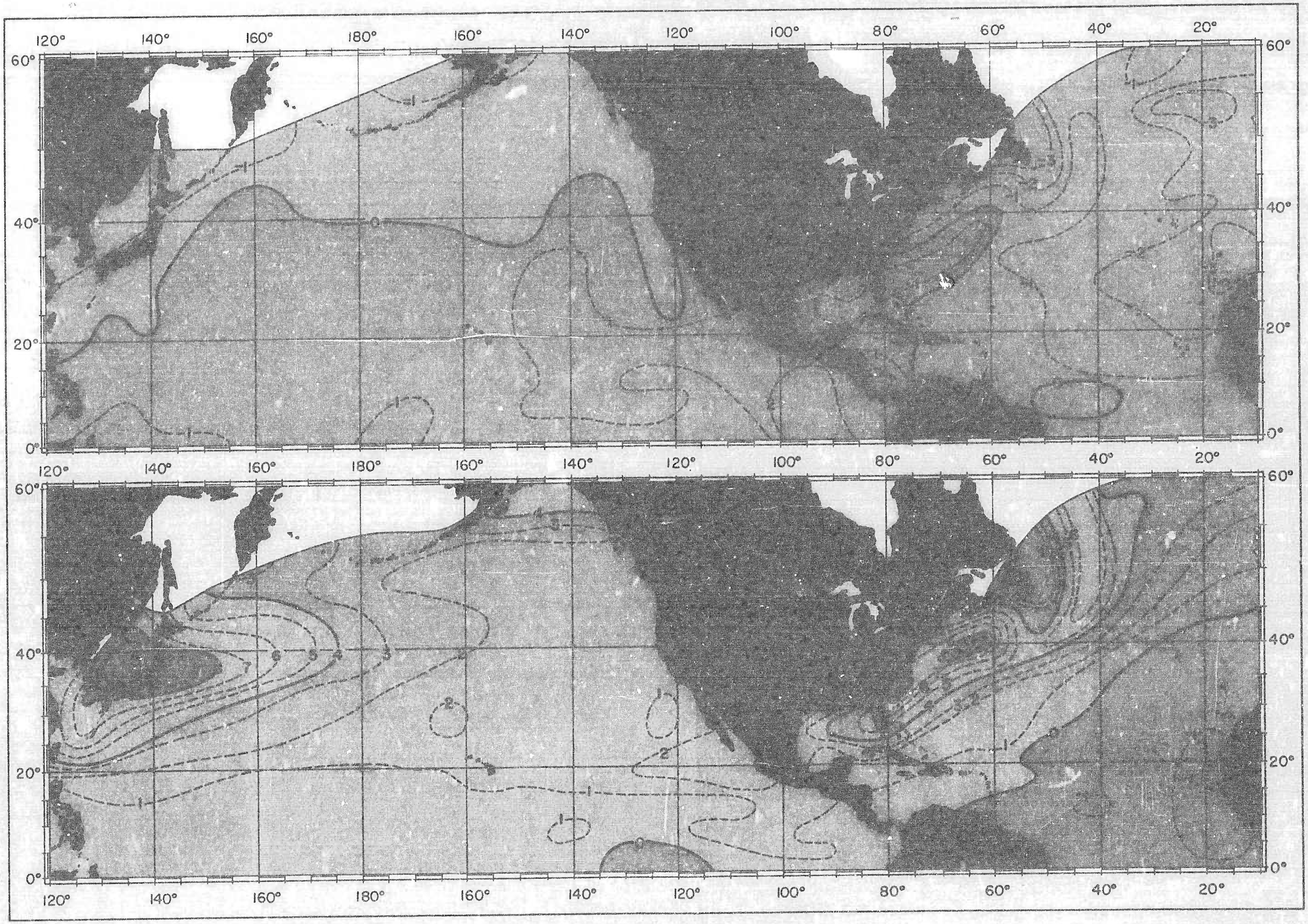


FIGURE 28. Chart showing the difference between water and air temperatures in the Northern Hemisphere, summer (above) and winter (below).

apparent that much of the time the sea surface is being cooled by evaporation, back radiation or conduction. Thus a very thin layer of water develops at the surface, which is cooler and therefore denser than the water just below, producing an unstable situation and causing the cool water to drain downward through the warmer water below. This convection process is generally accompanied by movement due to wind friction, and the effects of the two are not easily separable.

Studies of convective motion in the surface layer[3] were begun only a year or two before the war. Patterned motions in the surface of a lake were reported, and attention was drawn to the fact that floating gulf weed in the North Atlantic was sometimes distributed in lines extending up and downwind and sometimes scattered at random. It is strange that the long lines of gulf weed which are so common in the warmer areas of the North Atlantic had never before been connected with a patterned flow, involving alternating bands of convergence and divergence of the surface water. This can be pictured diagrammatically as in Figure 29. It follows then that when gulf weed is sufficiently plentiful so that some of it gets caught up in each convergence, an estimate of the thickness of the almost isothermal layer can be easily made. If the convection cells were circular in cross section, the crosswind spacing of the weed would be just twice the depth of the mixed layer. Actually the observations which are at hand indicate that the average ratio is nearer 1.8 and thus in Figure 29 the cells have been shown as being slightly compressed laterally.

Experiments with drifting bottles and observations of the orientation in relation to the wind of the floating jelly fish, Physalia, indicate[4] that the effect of the earth's rotation is to increase the vigor and width of the cells rotating to the right (in the Northern Hemisphere), so that the circulations on the average have the form shown in Figure 30.

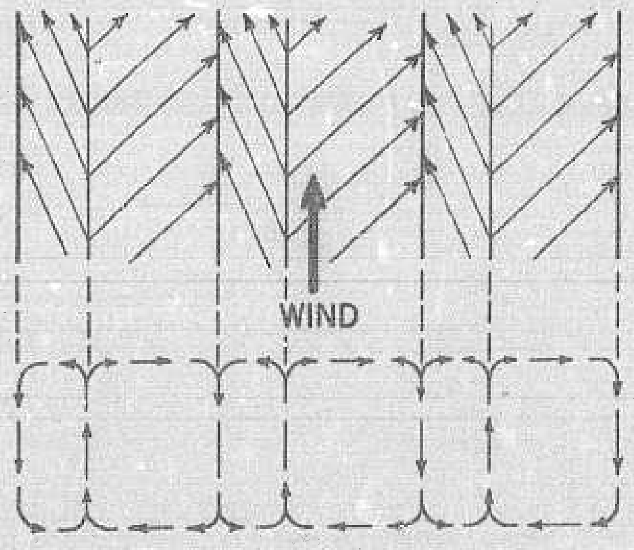


Figure 30. Asymmetrical convection cells.

Obviously the wind controls the orientation of these cells and contributes some of the energy required to maintain them. However, surface cooling is a critical part of the process. When the air is warmer than the water and when evaporation is low, well-developed convection cells are not encountered. How much surface cooling is required to initiate them is not known.

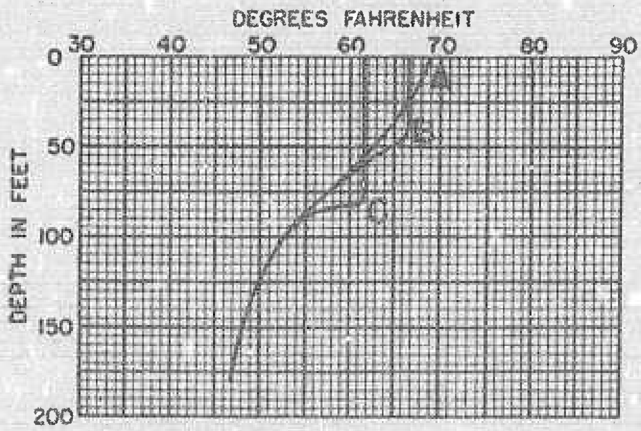
It is probable that at low wind velocities convection may take quite a different form, for it is a common sight in calm weather to find the gulf weed rafted together in roughly circular masses, indicating that the cooled surface water may be draining downward at scattered points in much the same manner that "chimneys" of rising air develop at low wind velocity when the air is being warmed from below. It also seems possible that beyond some critical maximum wind velocity, which probably varies with the rate of surface cooling, the patterned type of convective flow breaks down and the motions become random. But however this may be, it is clear that over a fairly wide range of wind velocities patterned convection plays an important part in maintaining a surface layer which is nearly isothermal vertically. The convective layer may be shallow and as a whole gaining in heat, as when diurnal warming is active, but as long as the surface itself is being cooled some form of overturn will be maintained.

If this general idea of convective motion is accepted, then for present purposes several general conclusions can be drawn, although it is admitted that these matters are not as yet on very firm ground:

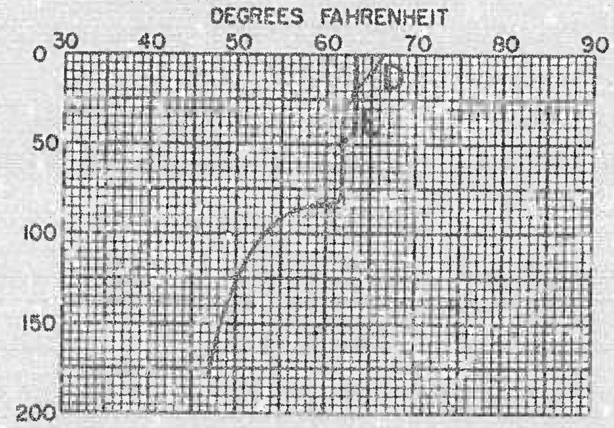
1. Convection will be most active where the humidity is at a minimum and where the air temperatures are lowest in comparison to surface temperatures (see Figure 28).

2. The more active the convection, the greater is the probability that a deep and virtually isothermal layer will be found at the surface; that is, temperature conditions will be favorable for echo ranging.

3. Within the convective layer, sheets of slightly colder, downward-moving water can be expected. Under some conditions this may be responsible for



A, stable surface layer;
B and C, stages in mixing.



D, surface heating and formation of a second stable surface layer;
E, continued mixing and secondary thermocline.

Figure 31. Diagram of wind-stirring.

the development of "microstructure," that is, small-scale vertical variations in temperature and salinity, which may have an unfavorable effect on echo ranging or at least make the strength of echoes highly variable. Further study of these factors will be required, however, before it will be possible to assess their practical value properly.

Effect of Wind

The amount of energy required to produce vertical mixing in the surface layer depends upon the density gradient. If this is negative, that is, if the density is greatest on top, the water is unstable and already has the potential energy required for vertical movement. If the density gradient is zero, in other words, if the water is of uniform density, a sufficient force must be applied to overcome the frictional resistance of the water. Finally, if the density increases with depth, the force required to produce vertical mixing must be strong enough to overcome the difference in weight between layers of water of different density. Thus, water whose density gradient is positive is highly stable. Nevertheless, such water is fairly susceptible to lateral movements which follow along the planes of equal density. Such horizontal motion entails friction between two layers of different velocity, and gradually water from the lower layer is dragged into the upper and vice versa. Thus, in time a positive density gradient can be weakened and destroyed by wind-generated frictional forces which at first acted only laterally.

In the absence of surface cooling, the wind, if it is sufficiently strong, is capable of forming or deepening a mixed surface layer. In other words, the frictional effect of the wind is important, whether or not it is aided by convection. A thermally stable surface layer once formed will be broken down by a wind, provided it blows hard enough and long enough. Especially in the latitudes of variable winds the effects of wind-stirring can be clearly seen on many BT records. In fact, with spring observations it is sometimes possible to interpret the record in terms of the winds during the past week or more.

A hypothetical case is illustrated in Figure 31. The initially stable situation (Curve A) was changed by a wind, first to Curve B and later to Curve C. There followed another period of warming and light winds so that Curve D developed. As the wind increased again this became Curve E. This is the explanation of much of the thermal variability at shallow depths.

It is important to notice in Figure 31 that as the mixed layer forms, the thermal stability just below increases. This same phenomenon will be evident during the autumn months in the diagrams showing the seasonal cycle, Figure 35 for example. The sharpness of the upper part of the thermocline increases as the depth of the mixed layer increases as a result of local cooling and wind-stirring, and this is of importance in considering layer effect.

The effect of the wind in maintaining or deepening an isothermal surface layer is complicated by the fact that the wind also sets up a current near the surface which may remove the mixed water from a given area almost as fast as it is formed. Presumably such a current requires some time to develop (see Section 7.1.4), while the effect on vertical mixing is more im-

mediate. Thus, brief and variable winds are usually responsible for the effects illustrated in Figure 31.

Waves and Wave Transport

Waves are among the most obvious of marine phenomena, and they have always had a direct and noticeable effect upon ships, as any ocean traveler knows. Antisubmarine ships are no exception, and especially in the case of smaller vessels, the motion produced by the waves may be a serious deterrent to efficient echo ranging. In addition, the process of echo ranging itself is affected and sometimes markedly impaired by the noise of breaking waves and by quenching effects.

Aside from their direct effects on echo ranging, waves play an important indirect role through their influence on local oceanographic conditions. To understand these effects it is necessary to examine some of the simple properties of wave motion.

In its simplest form a wave is a regular, progressive displacement of the surface from its mean level. However, the actual appearance of the open sea seldom gives any impression of rhythmic regularity. The picture is frequently one of apparently random movement and chaotic disorder. Elevations and depressions of various shapes and sizes appear and disappear; some are superimposed upon others; they may travel at different speeds and even in different general directions. Nevertheless, the deformation of the surface at any given place and time may, with some allowance for turbulence, be thought of as the combined result of some finite number of relatively simple wave trains of varying periods, amplitudes, velocities, and crest lengths.

A simple wave can be completely described by three or, at the most, four measurements. First there are the wave length, which is the distance from crest to crest or from trough to trough, and the wave period, which is the time in seconds required for the passage of one wave length. The ratio of these two quantities gives, of course, the speed of the wave. Then there is the height of the wave from trough to crest. Finally there is the crest length. For most waves, the crests (and troughs) are assumed to be of indefinite length. There exist, however, both in theory and in fact, waves whose crests are broken up into regular segments separated by segments of troughs. To describe such waves fully one must specify the length of these crest segments. This is the crest length and such waves are called *short crested* waves.

Below a certain very low speed the wind can blow without causing so much as a ripple. Once a rising wind has begun to form waves, it will increase their size and speed rapidly by a combination of pressure on the windward slopes and suction on the lee. The speed of waves so propelled is obviously limited by the speed of the wind, and observations indicate that generally the largest waves have a velocity about eight-tenths that of the wind.

The limit to a wave's steepness is relatively low. Unless the length of a wave is at least 7 times its height, the wave will break. Waves may reach the breaking point either through the action of the wind or through reinforcement by some other wave train of different period. Whenever waves break, or even approach breaking, the simple wave form is distorted and there is a marked degree of turbulence. A wind of force 5 (Beaufort) or more augments this mixing effect by blowing the wave crests across the trough ahead in the form of spume.

With a rising sea, waves of various lengths are present. The smallest waves break at low wind velocities, while the longer ones remain and attain a greater height, their size being finally limited by the velocity and duration of the wind and the distance traveled. The tendency of waves to increase in length with the distance traveled and for their speed to increase correspondingly may occasionally lead to the surprising result that the swell following a storm has a higher velocity than the wind which originally produced it.

If an observer at sea watches a gull or other object floating on the water, he will see that as a wave passes, the movement of the object is not merely up and down but rather it describes a roughly circular or elliptical orbit, in such a manner that at the crest the object moves forward with the wave and in the trough it is moving in the opposite direction. Particles of water in the wave move in somewhat similar orbits. Furthermore, the movement occurs not only in particles of surface water but also in those some distance below the surface. The orbits of movement are bigger for large waves than for small, but for any wave the size of the orbit and the velocity decrease rapidly with depth, approaching zero at a depth of more than half a wave length below the mean surface level.

The fact that the velocity decreases continuously with depth prevents the orbits from being completely closed circles. That is, a water particle travels faster in the upper part of its orbit than in the lower, and

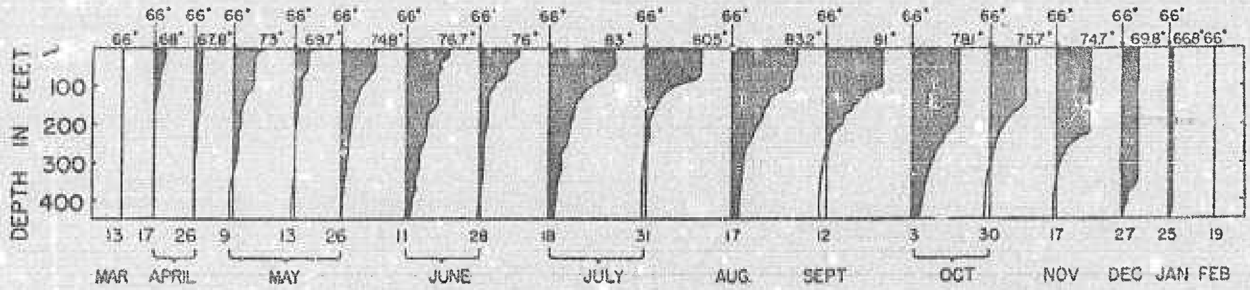


FIGURE 32. Typical bathythermograms showing seasonal temperature cycle in the Bermuda area.

so after having completed one revolution does not return to the point from which it started but to a point slightly farther forward. Thus there is a transport of water in the direction of the waves' progress.

The rate of this forward transport is greatest at the surface and decreases rapidly with depth. The total volume transport is dependent on the wave's length and height. With a very low wave in deep water it is negligibly small. With larger waves the transport is probably of the same order of magnitude as wind driven currents.

In summarizing the effects of waves on the temperature structure of the ocean it is important to compare the direct effects of wind and the indirect effects resulting from wave motion. In each case there is mass transport of water, caused on the one hand by the frictional drag of the wind, and on the other by the character of the movement of water particles in the wave. Both are therefore capable, by transporting surface water, of producing zones of convergence or divergence, accompanied by raising or lowering of the thermocline, which alters diving and sound conditions locally. Or they may be responsible in some cases for water of one temperature being carried over water of another. If the water on top is cooler than that below, marked convection will result. If it is warmer there will be stable stratification.

Both wind and waves are also capable of altering sound conditions by causing vertical turbulence. Mixing by the wind results both from convection and from frictional drag caused by the horizontal transport of water. Mixing by waves occurs chiefly when they break; there is no evidence to indicate that wave transport produces a measurable amount of turbulence.

Thus wind and waves have very similar effects on oceanographic conditions and echo ranging, although the effects are produced in quite different ways. Because they are so similar, the effects are not easily separable, and quantitative investigations have only just begun.

5.2.2 The Seasonal Thermocline

General Description

We have seen that, except for the short-lived negative temperature gradients of diurnal warming, convection and wind-mixing usually maintain a surface layer of substantially isothermal water. However, during the time of year that insolation markedly exceeds heat losses, this mixed layer seldom extends down to the main thermocline. This is partly because convection is efficient only to the depth that the water is unstable, or at least of uniform density, and partly because during that time of year winds are ordinarily mild. In any case, as the surface water gradually grows warmer with the advance of spring, there develops, immediately below the depth to which convection and wind-mixing remain effective, a secondary thermocline. If the temperature of the layer above this thermocline continues to rise, the thermocline itself will grow steeper and become more of a barrier to downward mixing.

A typical seasonal thermal cycle in mid-latitudes is shown in Figure 32 by a series of bathythermograms taken in the Bermuda area and in more diagrammatic form in Figure 33. In midwinter the water column is essentially isothermal from the surface to the top of the main thermocline (Figure 33A). Starting in March the surface water begins to warm, and the depth of wind stirring is at once markedly decreased (Curve B, Figure 33). Thus in spring the water column from top to bottom consists of the following parts: (1) a relatively shallow, wind-stirred surface layer which is rapidly increasing in temperature, (2) a relatively shallow layer of transition, the seasonal thermocline, (3) an isothermal layer which retains midwinter temperature, (4) the main thermo-

cline, and (5) the deep water. Until midwinter again these five subdivisions can be made out in any temperature-depth curve in mid-latitudes. In high latitudes there is, of course, no permanent thermocline, and in the tropics because of the small seasonal change it is difficult to distinguish between the permanent and seasonal thermocline. By midsummer over the greater part of the oceans, surface warming and vertical turbulence have increased both the depth and the magnitude of the seasonal thermocline (Curve C, Figure 33). During the autumn (Curve D, Figure 33) cooling at the surface and the resulting tendency for instability rapidly increase the thickness of the wind-stirred surface layer. The seasonal thermocline also deepens rapidly, but at the same time it decreases in magnitude, only to vanish as the simple midwinter conditions are restored.

By comparing Figure 33 and Figure 14 it will be seen that the seasonal cycle bears a marked resemblance to the diurnal cycle, if the change in scale be neglected. Thus the curves for winter and night, for spring and morning, for summer and afternoon, and for autumn and evening are each of very similar shapes.

Obviously, seasonal changes are at a minimum near the equator. Furthermore, the changes do not come simultaneously over the whole ocean basin, but work gradually northward and southward with the sun. An additional complicating factor is that the winds are not steady outside the trade-wind belt so that the development and the decay of the seasonal thermocline do not always proceed steadily. Nevertheless, once the seasonal thermocline has been well established (by May, for example, in mid-latitudes) it will not disappear, no matter how great or how many the storms, until late in the autumn. This fundamental quality of a thermocline, namely, that it has stability and can thus resist vertical turbulence, should be borne in mind throughout the reading of this report.

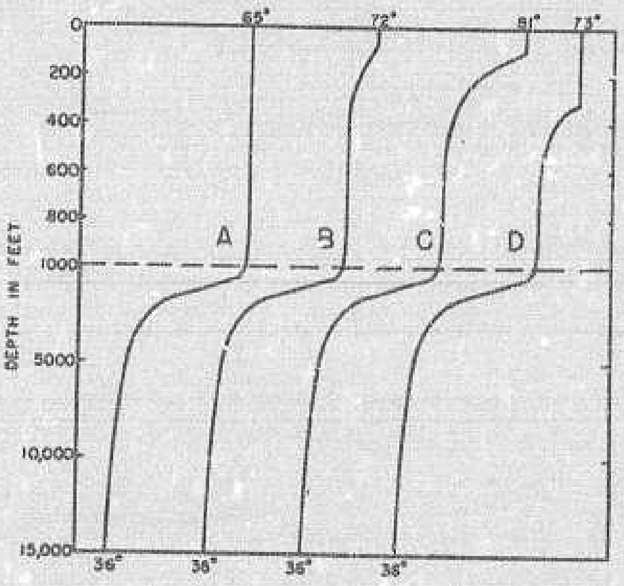


FIGURE 33. Diagram of seasonal thermocline in the Bermuda area. A. Winter. B. Spring. C. Summer. D. Autumn.

Geographical Factors

The main (or permanent) thermocline is responsible for the vertical temperature gradients encountered by a deep submarine over only a rather small fraction of the total ocean area, chiefly in the tropics. The influence of the seasonal thermocline, on the other hand, is very widespread.

This leads to an analogy which can be drawn between land warfare and subsurface warfare, and which may serve at this point in the discussion to clarify somewhat the roles of the various types of thermoclines. In land fighting, as is well known, soldiers are very conscious of two factors: the weather and the terrain. In subsurface warfare the weather also plays an important part in that by controlling diurnal warming it determines the temperature gradients at and near projector level. These in turn determine the refraction pattern and thus the general sound conditions. But there is also in the sea a physical structure analogous to terrain in land warfare. The seasonal thermocline, because of layer effect, is comparable to a hill behind which a submarine can hide. At times and at places where the seasonal thermocline is sharp and well developed, by submerging to below the isothermal surface layer a submarine may be able to gain very considerable cover. Other parts of the sea, from this standpoint, because of the absence of vertical thermal gradients, are comparable to a level plain in land warfare. This is a rather new and far-reaching conception. It means that both the submarine and her adversaries will find it an advantage to know the subsurface temperature distribution much as a soldier has to know the topography, both for local cover and for strategic planning.

One can gain a good picture of the magnitude and geographical variations of the seasonal thermocline merely by subtracting midwinter surface temperatures from midsummer surface temperatures. The

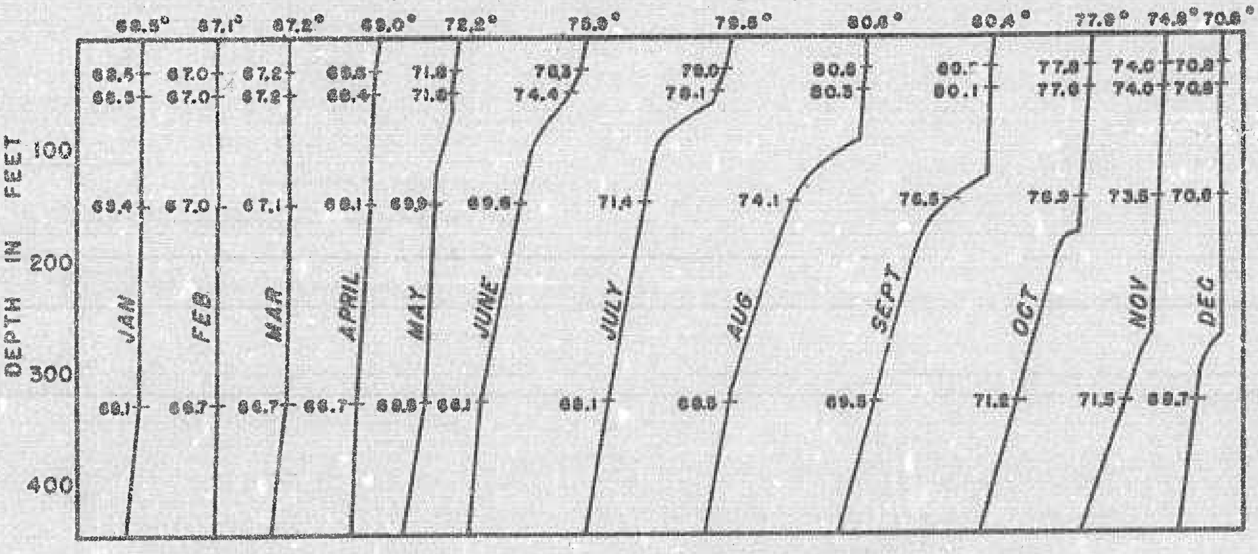


FIGURE 35. Seasonal cycle in the Bermuda area—average monthly temperature-depth curves.

resulting chart, Figure 34, shows, as would be expected, that the greatest seasonal change occurs in mid-latitudes, especially in the western parts of the oceans where the prevailing winds are off the continents. It will also be noticed that in those areas in the equatorial regions where the seasonal thermocline is less than 2.5 degrees the main thermocline is largely above the depth of 600 feet (see Figure 8). In these areas, therefore, the main thermocline rather than the seasonal is of major importance in determining layer depth and there is comparatively little change throughout the year.

The fact that the seasonal thermocline so dominates the vertical temperature distribution at depths critical for a modern submarine greatly increases the difficulty of getting out practical charts of either the sound or the diving conditions. Since seasonal changes are continuous, though more rapid in spring and autumn, it is sometimes misleading to group observations for periods even as short as a month.

THE SEASONAL PROGRESSION

There are two quite different ways in which the available data can be plotted to demonstrate for our present purposes the significant points in connection with the seasonal temperature cycle. It is possible to show average monthly temperature-depth curves (Figure 35, for example), or it is possible to plot iso-

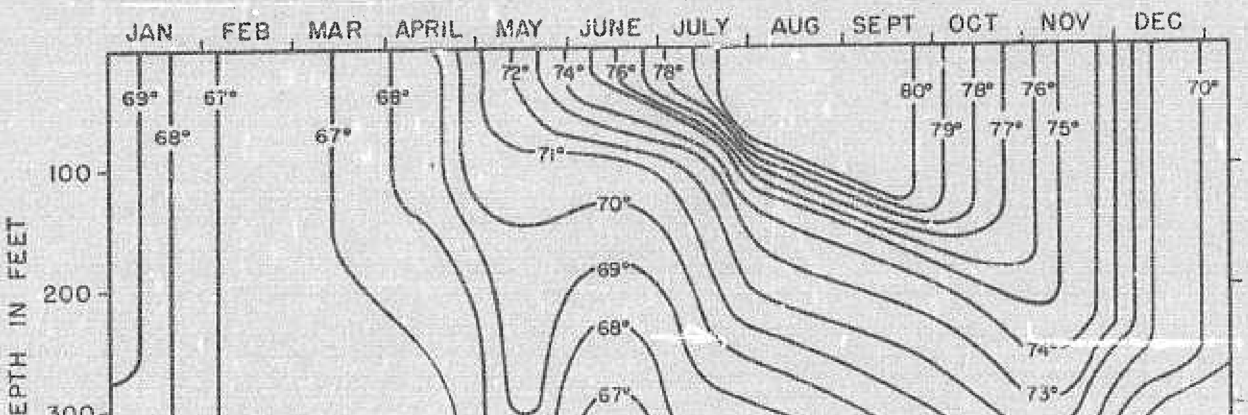


FIGURE 36. Seasonal cycle in the Bermuda area—average isotherms.

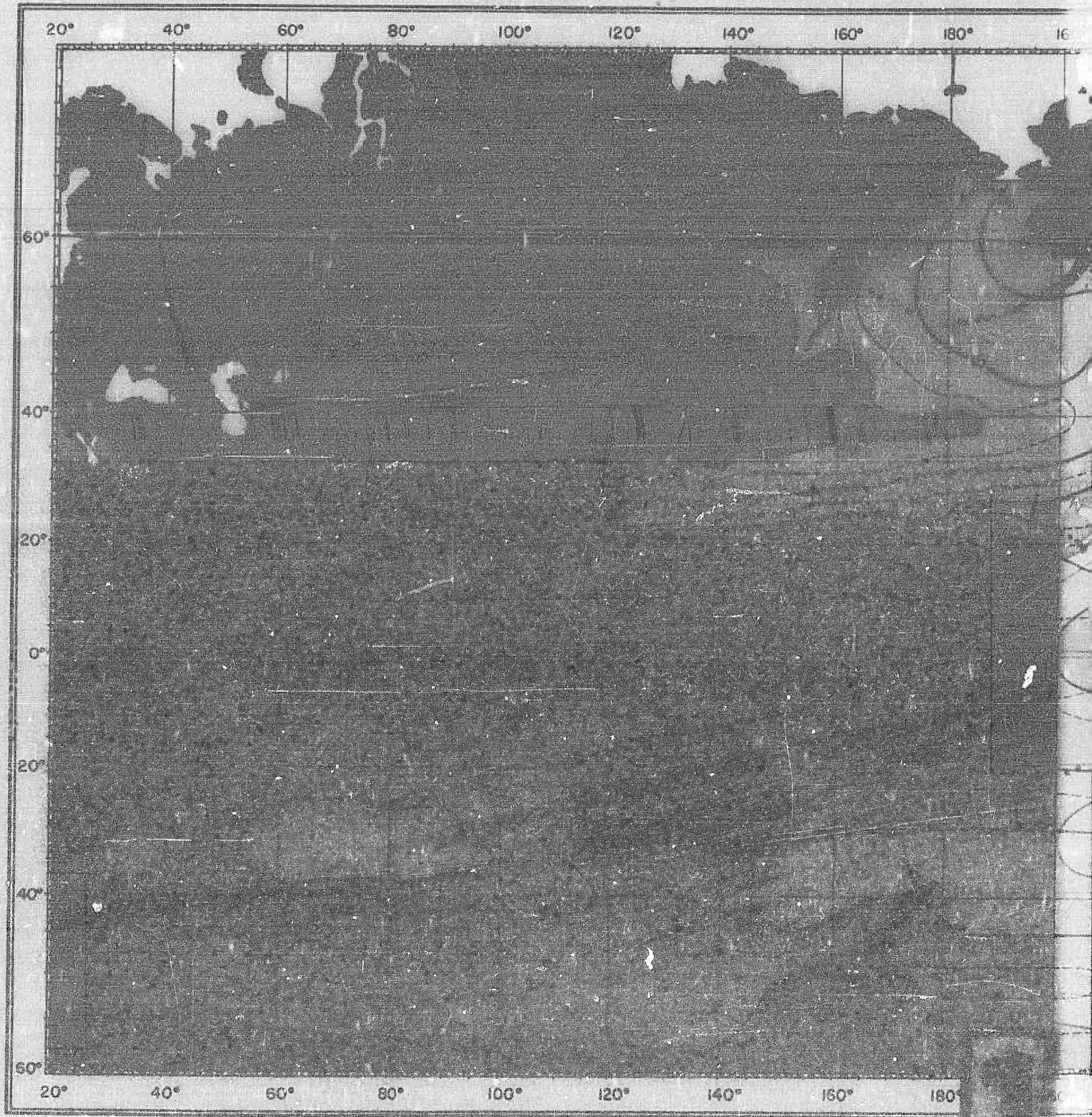


FIGURE 54. W

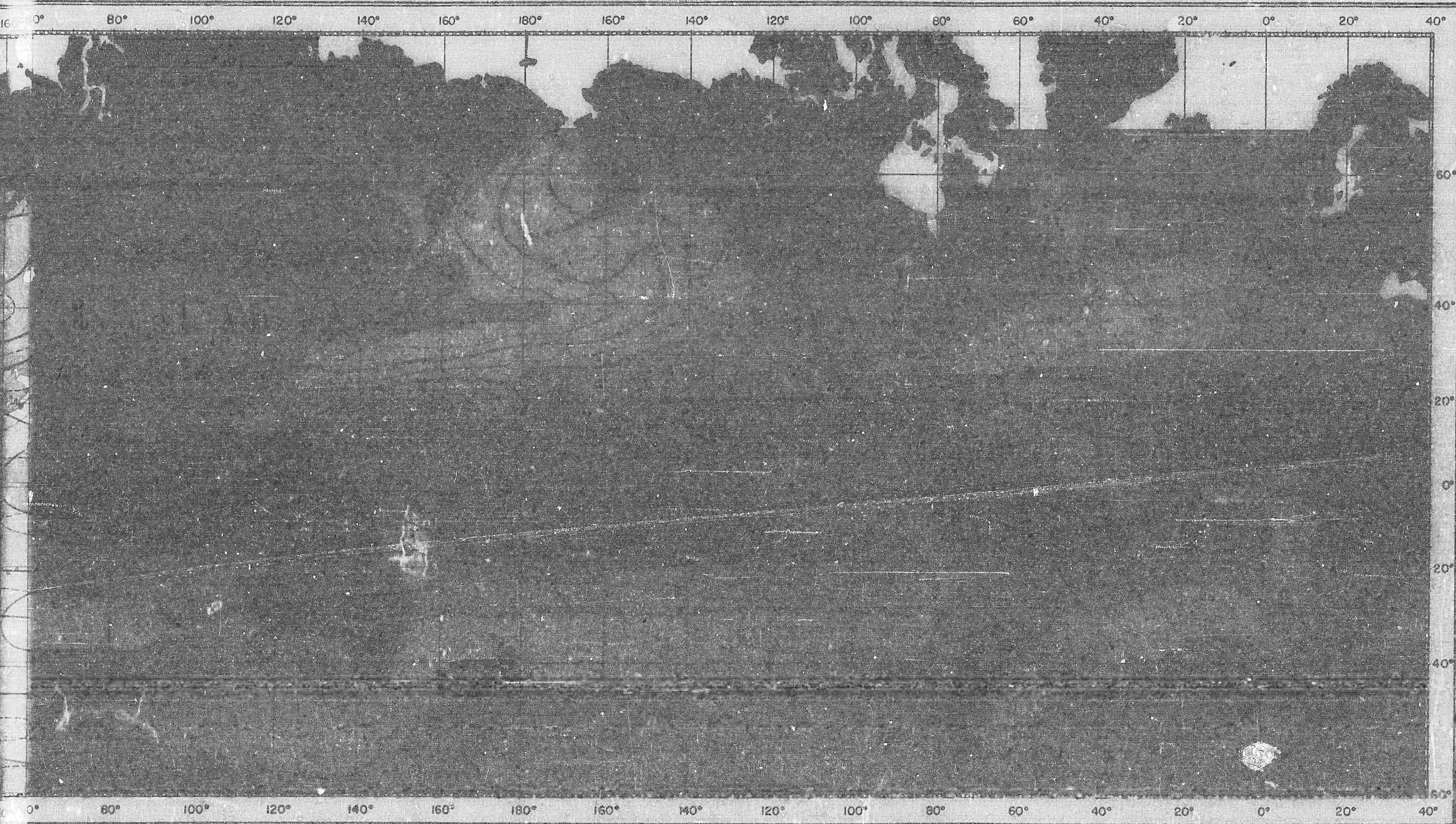


FIGURE 34. World chart showing summer minus winter surface temperatures.

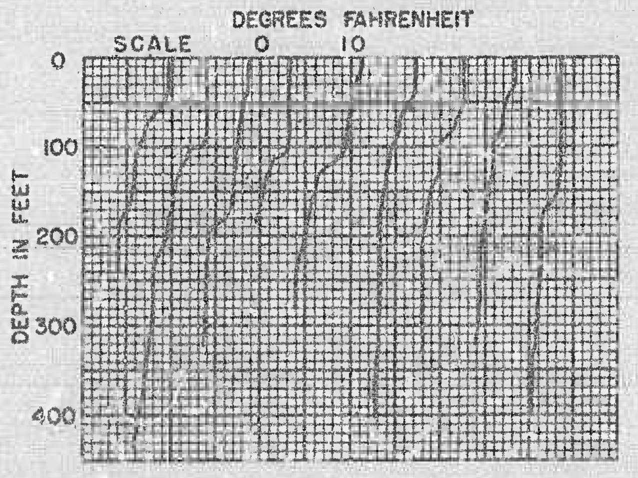


FIGURE 37. Variability in individual bathythermograms in the Bermuda area in April.

therms with depth and time as coordinates (Figure 36). Both methods have certain advantages and disadvantages.

The figures show the available data from near Bermuda and are typical of the seasonal changes over wide areas of the warmer waters of the western North Atlantic. The temperature-depth curves (Figure 35) show the average of the available BT data and therefore indicate the type of conditions most likely to be encountered. Some variation in individual bathythermograms is to be expected. To give some idea of the degree of variability in the Bermuda area a selection of the observations for April has been plotted in Figure 37.

It will be noted in Figure 35 that from May through August on an average the warm surface layer is thermally stable (surface temperature minus the temperature at 30 feet is greater than 0.3 F) to a degree which would limit the maximum range on a shallow target. This tendency for negative gradients near the surface in the summer reflects the rather moderate winds near Bermuda at this particular season, plus the rapid warming due to clear skies. For example, of the 360 bathythermograms available from May to August in this area, 65 per cent show an isothermal surface layer varying in depth between 40 and 100 feet, while 35 per cent show thermal stability at and near projector level. The average curve then will be one having weak negati.. temperature gradients near the surface, and this is somewhat misleading. The same applies to a lesser degree to September.

If the observations were more numerous, only bathythermograms taken at night or during periods of strong winds might be used to develop average temperature-depth curves and in this way the effects of diurnal warming could be eliminated in such a diagram as Figure 35. However, as yet there are too few observations from most months to make this desirable. On the other hand, in Figure 36, since isotherms for only every one degree are used, the effects of diurnal warming are eliminated. Nevertheless, from this type of diagram it is somewhat more difficult to judge the refraction pattern.

Figures 38 and 39 show the same kind of graphs for the seasonal cycle in mid-latitudes in the Pacific.[a] The differences between these two temperature cycles are very slight. The depth of the winter mixed layer appears to be slightly greater in the Atlantic than in the Pacific, and the development of the seasonal thermocline in spring is perhaps less regular. Both these differences are due at least in part to the fact that in the area of the Atlantic chosen for analysis the frequency of winds of gale force is 10 to 20 per cent greater during the winter and spring months than in the Pacific area. It is reasonable to suppose that when observations from more regions have been analyzed,

[a] Figure 38, like Figure 35, was prepared by plotting the average temperature differences from the surface to certain fixed depths and then making the main break in each curve occur at the average layer depth. The bathythermograms for Figure 38 were read at fewer depths than those for Figure 35, and so no attempt has been made to join the points by a smooth curve.

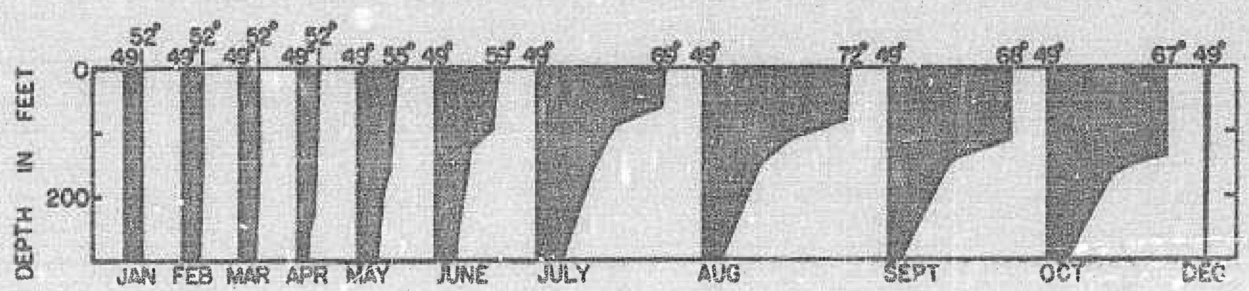


FIGURE 38. Seasonal cycle in mid-latitudes in the Pacific—average monthly temperature depth curves.

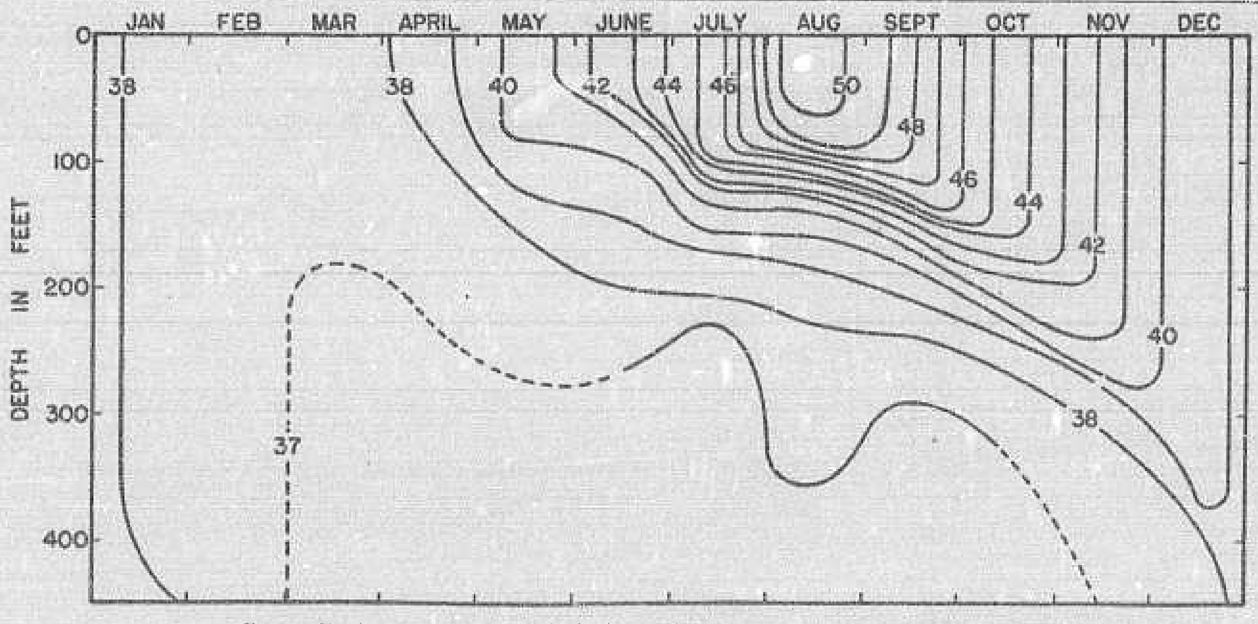


FIGURE 39. Seasonal cycle in mid-latitudes in the Pacific—average isotherms.

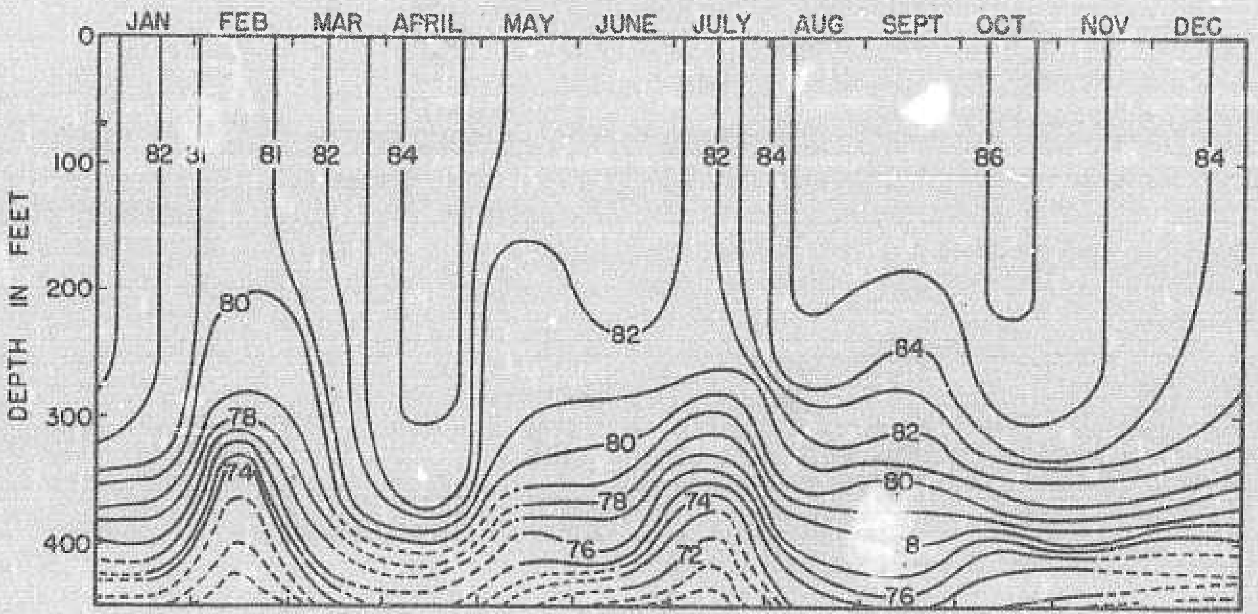


FIGURE 40. Seasonal cycle in the equatorial Pacific—average isotherms.

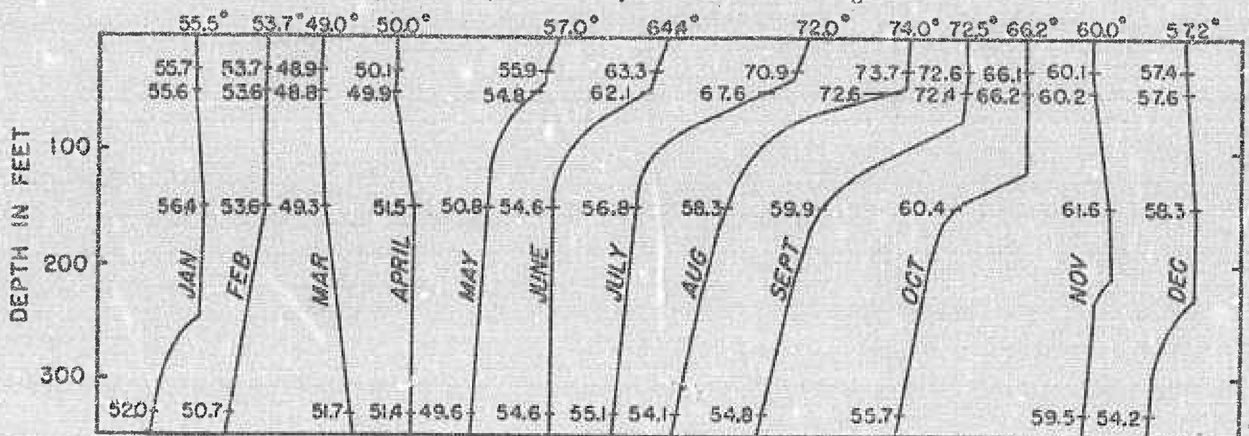


FIGURE 41. Seasonal cycle over the continental slope of the western North Atlantic—average monthly temperature-depth curves.

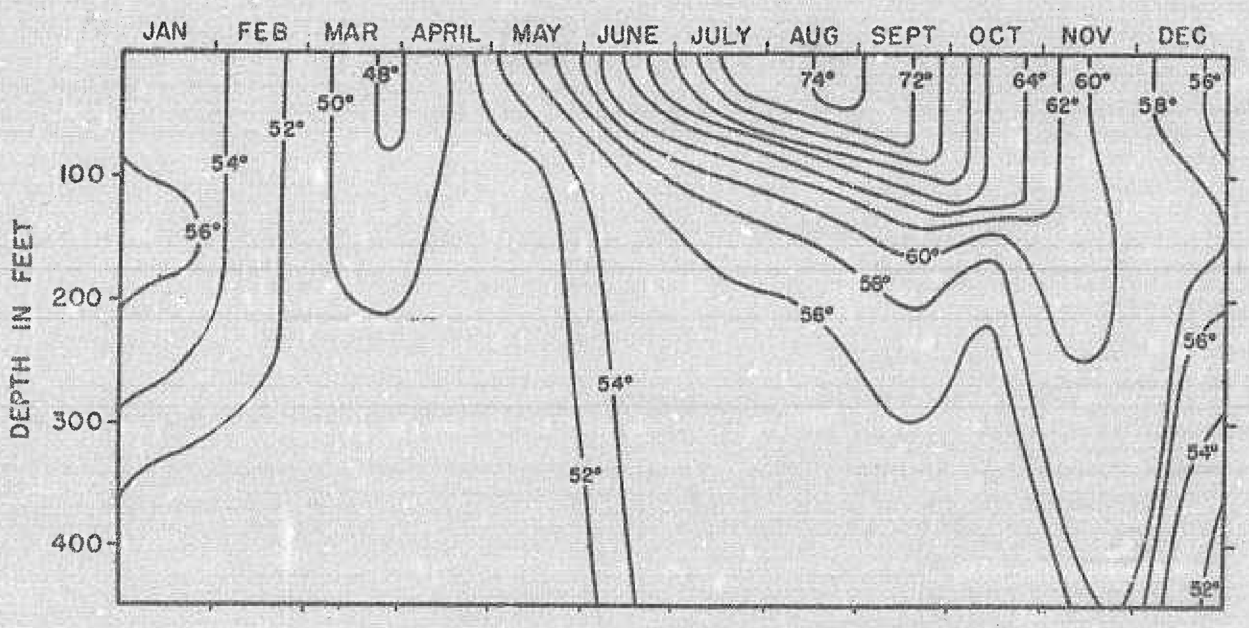


FIGURE 42. Seasonal cycle over the continental slope of the western North Atlantic—average monthly isotherms.

many such minor differences in seasonal cycles will be found, which can be correlated with local climatic variability.

In the trade wind belt the magnitude of the temperature change between winter and summer becomes less pronounced than it is in mid-latitudes, but the pattern of the change is in other respects very similar. The annual temperature change becomes least near the equator and may be no more than 4 or 5 degrees, as shown in Figure 40. Here the form of the seasonal cycle is quite different from those previously described, for there is a bimodal seasonal curve, with the highest temperatures occurring in April and in October slightly after the time when the sun has passed directly overhead.

Going to the opposite extreme, very marked seasonal cycles are found in the higher latitudes not far from land. This is shown in Figures 41 and 42, in which observations from between the northern edge of the Gulf Stream and the continental slope in the sector off southern New England have been plotted by the same methods previously used. Here the maxi-

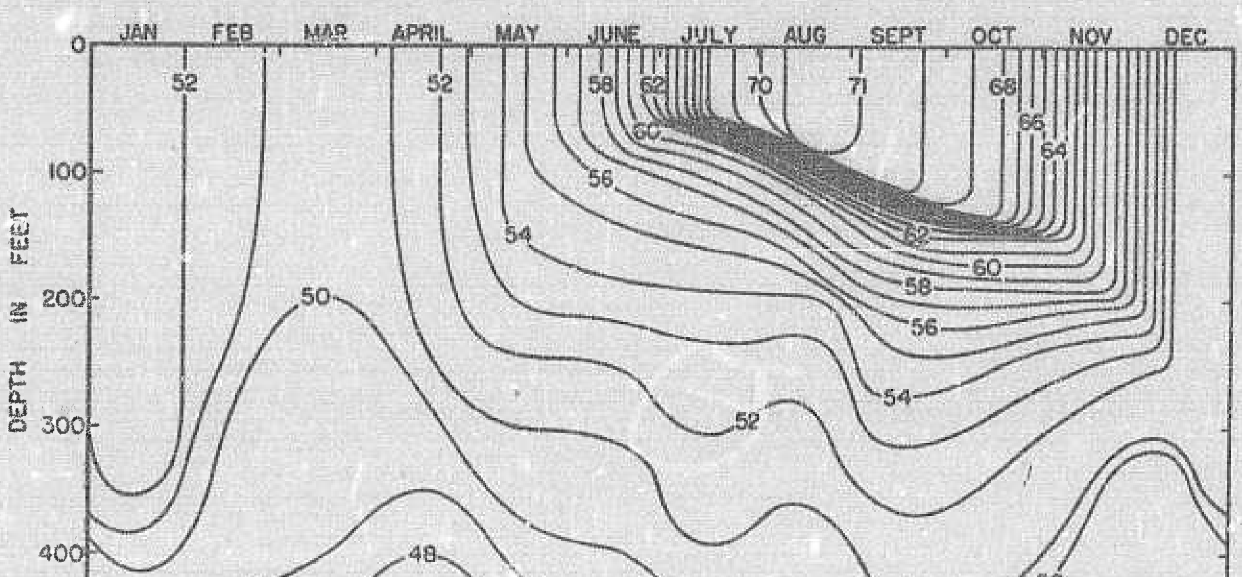


FIGURE 43. Seasonal cycle Aleutian area—average monthly isotherms.

mum temperature difference between summer and winter is of the order of 26 degrees as compared with about half as much as is shown in Figures 35 and 36.

In high latitudes and at greater distances from the continents the seasonal changes become less pronounced again; this reflects the smaller range in surface temperature (see Figure 34) and the stronger winds. Unfortunately the available observations are too few from any one area in high latitudes to demonstrate the complete annual cycle. The best data are from the Aleutian Islands area (Figure 43) and, as would be expected, emphasize the shorter summer season.

It is hoped that this small sample (Figures 35-43) will have served to illustrate the development and the decline of the seasonal thermocline in the open ocean. It would require a great many such diagrams to illustrate the slight differences encountered from region to region. When the number of BT observations becomes sufficient to permit this to be done in considerable detail it will be possible to improve the charts of average echo ranging conditions.

Chapter 6

RELATIONSHIP OF SALINITY AND TEMPERATURE

6.1 TEMPERATURE-SALINITY CORRELATION IN THE DEEP WATER AND IN THE MAIN THERMOCLINE

In the surface waters the relationship between temperature and salinity is highly variable since it is affected by surface heating and cooling, evaporation, and precipitation. In the main thermocline and the deep water layer, however, the temperature-salinity correlation remains nearly constant within large areas. Knowing the temperature *in situ*, one can predict the salinity of a sample of water with almost as much accuracy as it is measured by the routine process ($\pm 0.02\ ^0/_{00}$). This is illustrated by Figure 1 in which the observations having temperatures colder than 66 F from nearly all the available oceanographic stations in the central part of the North Atlantic have been used. But when the water masses from widely different areas are compared, slight differences in the temperature-salinity correlation can be distinguished. For example, the bottom water originating in high southern latitudes of the Atlantic has a salinity of about $34.8\ ^0/_{00}$ as compared with about $34.9\ ^0/_{00}$ in the North Atlantic. Such small but persistent differences provide oceanographers with an excellent method of tracing the slow water movements in the main thermocline and below. However, for our present purposes it is to be concluded that as long as a submarine is operating in the main thermocline, the density can be predicted with very satisfactory accuracy merely by observation of the temperature.

It will also be seen from Figure 1 that as the temperature increases, the salinity also increases. It follows then that within the main thermocline salinity decreases with depth. This is the general rule in the open ocean and, as will be discussed in more detail below, is in marked contrast to the conditions in coastal waters where nearly always salinity increases with depth.

From the point of view of the stability of the whole water column in the deep ocean, the vertical distribution of salinity tends to decrease slightly the stability due to temperature alone. In other words, if there were no decrease in salinity with depth, density would increase with depth slightly more rapidly. However, the vertical salinity variations are so minor that at a typical oceanic station at depths below the top of the main thermocline the observations for temperature and density fall along nearly parallel curves when suitable scales are chosen (Figure 2). It should be pointed out also that at depths where the vertical

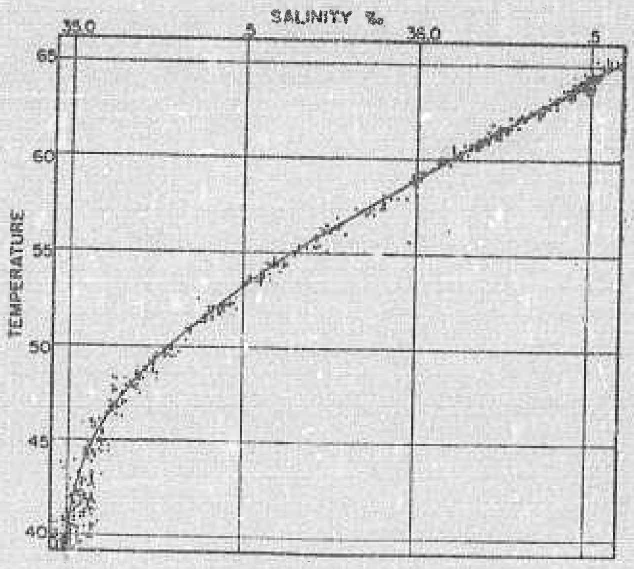


Figure 1. Temperature-salinity correlation in mid-Atlantic.

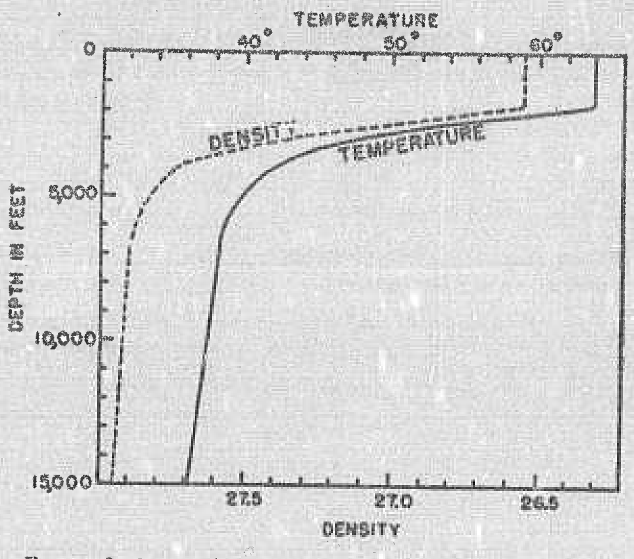


Figure 2. Comparison between temperature-depth and density-depth curves in the mid-Atlantic.

temperature gradient increases, the vertical salinity gradient also increases.

It will be seen from Figure 1 that in the central basin of the North Atlantic the waters at mid-depths are slightly fresher than would be the case if they were formed locally by the mixture of surface and bottom water. This situation also occurs in the other oceans near the axis of the main thermocline and is even slightly more pronounced. It is explained by the fact that when the stability is great, lateral mixing is more effective than vertical mixing. This is similar to the phenomenon described in connection with the establishment of temperature gradients, in which a force sufficient to overcome the frictional resistance of the water will cause mixing in water of uniform density, but a greater force is required to destroy density differences. Therefore when there are density gradients, most mixing occurs laterally following the surfaces of constant density. Thus the temperature-salinity correlation at mid-depths can be explained by following the surfaces of constant density north or south until they intersect the sea surface. In short, they have the temperature and salinity characteristics they acquired at or near the surface in midwinter in the higher latitudes, and in the course of their transport to the main thermocline region of the central basins they have been little modified by vertical mixing.

6.2 SALINITY GRADIENTS NEAR THE SURFACE

Salinity gradients arise (1) from the dilution of the surface by rainfall, melting ice, and the runoff from the land, (2) from evaporation of water from the sea's surface, and (3) from the flow of waters of different salinity over one another as the result of ocean currents.

In temperature regions above latitudes 40° N and S there is usually an excess of rainfall over evaporation and consequently positive salinity gradients tend to develop beneath the sea's surface. Along the coasts of such regions the outflow from rivers very greatly augments this effect and substantial density gradients result from the dilution of the upper layers of water. It follows that the shallow temperature gradients characteristic of temperate regions in summer are accompanied by salinity gradients. These gradients are particularly strong in coastal regions. Both kinds of gradient cause the water to be more dense as

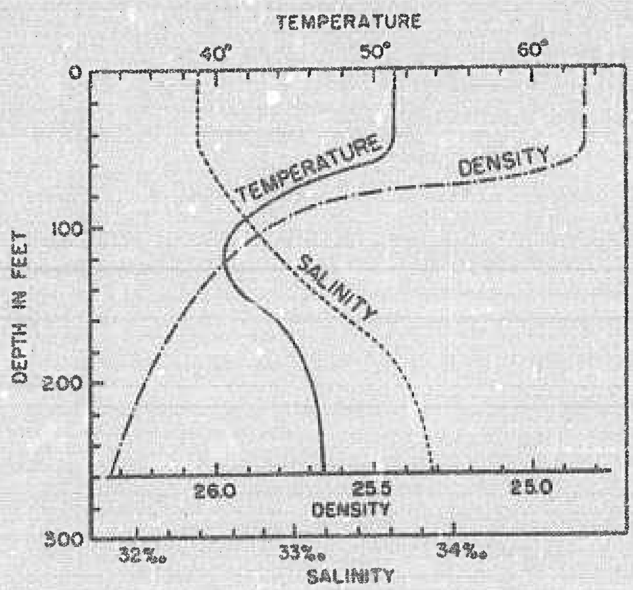
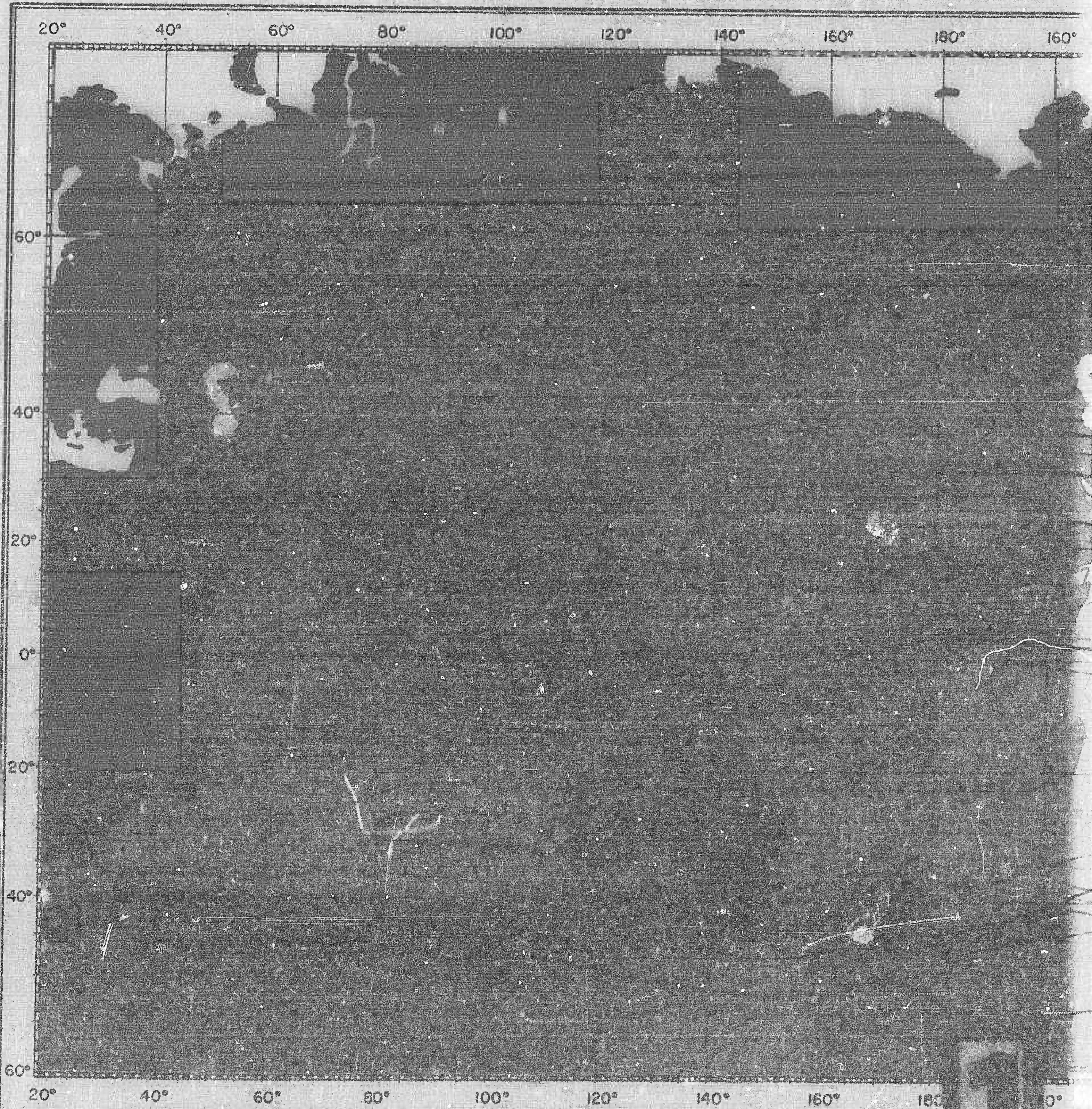


FIGURE 3. Vertical temperature, salinity, and density curves in coastal waters.

depth increases, that is, they supplement one another in developing the stability of the water column.

It may be observed from Figure 3, which shows the gradients of temperature, salinity, and resulting density in a situation of this sort, that the gradients of temperature and salinity very closely coincide in depth. Where the temperature gradient is strongest the salinity gradient is strongest also. This arises because the surface waters are prevented from mixing with the deeper waters by the sharp density gradient while both above and below, the water mixes more freely. Both gradients consequently tend to develop in the same relation to the resulting density pattern. During the winter, when the disappearance of the temperature gradient decreases the stability of the water, the mixing which results also destroys the salinity gradient. In spring the melting of snows and the rainfall characteristic of the season led to the early development of the salinity gradient. This becomes relatively less important than the temperature gradient in determining the density distribution as the summer season advances.

In the warm oceanic areas salinity gradients are less pronounced and are thus of less importance in determining the density distribution in the upper layers of the sea. In the central basin of the North Atlantic, near the borderline between temperate and subtropical waters, seasonal changes in evaporation and precipitation can produce slight vertical salinity gradients at relatively shallow levels. As an example,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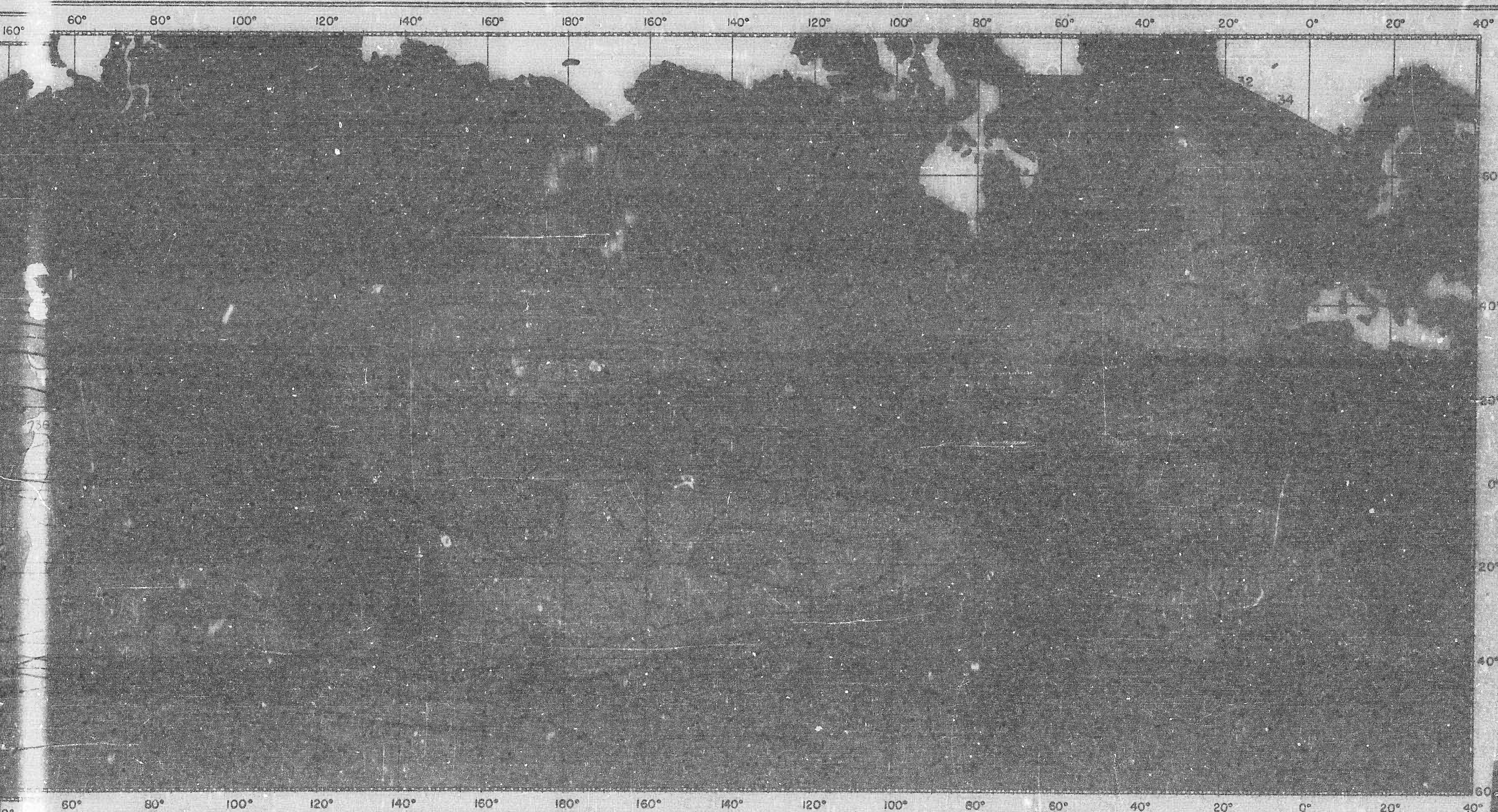

FIGURE 4. World chart of surface salinities—June, July, August.

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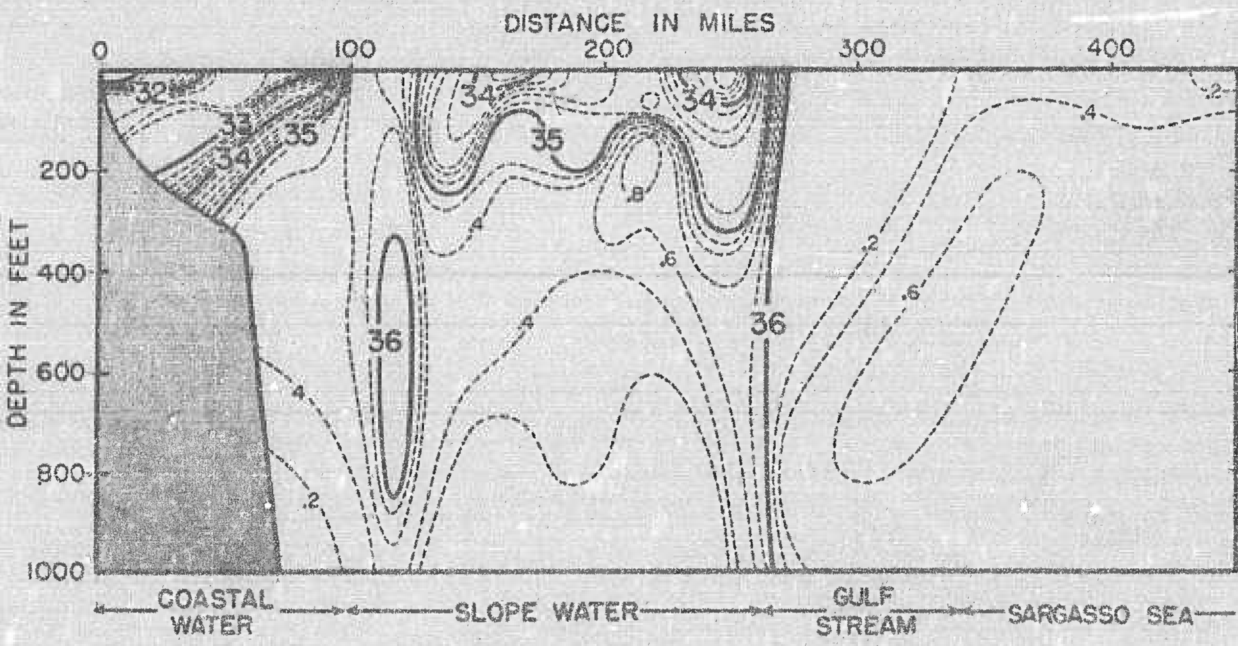


FIGURE 5. Salinity profile, Montauk Point to Bermuda.

the surface salinity in the Bermuda area averages close to 36.6 ‰ in winter when strong and relatively dry winds prevail, but in summer the damper, weaker winds permit the surface layer to freshen to about 36.1 ‰. The resulting slight increase of salinity with depth occurs at about the same level as the summer thermocline, so the effect on sound is negligible. However, for this reason, as well as because of the seasonal thermal cycle at the surface, the temperature-salinity correlation is by no means constant at depths above the top of the main thermocline.

In substantial areas of small rainfall in the subtropics evaporation exceeds precipitation, and the most saline water is found at the surface. Such salinity gradients are small and are associated with similarly small negative temperature gradients, with the result that the density of the water column is nearly uniform. On the other hand, near the equator the high rainfall of the doldrum belt reduces the surface salinity and makes it considerably fresher than the water near the top of the main thermocline. The latter, as has been shown above is relatively shallow in these latitudes, hence both temperature and salinity contribute to the very high stability near the surface.

Thus it is apparent that the distribution of salinity in the surface waters shows slight but distinct variations which are controlled by climatic factors and hence have pronounced seasonal and geographical characteristics. The latter differ somewhat from those of temperature. In general, temperature at the surface decreases with increasing latitude. Surface salinities reach their maximum in a belt centering at about latitude 23°, along the outer edges of the trade winds where the air is descending and relatively dry and where evaporation is greater than either nearer the equator or in high latitudes. This is illustrated in Figure 4, which is a world chart of midwinter surface salinity.

6.3 AREAS OF VARIABLE SALINITY GRADIENT NEAR THE SURFACE

When the surface waters of a warm, saline current mix with those of a colder and less saline current, as occurs off the Grand Banks of Newfoundland, to cite what is probably the extreme example, the temperature-salinity correlation becomes very variable indeed. At times water as fresh as 32 ‰ may be just above or immediately next to water of salinity greater than 36 ‰. In the latter case the difference in color of the two contrasting water masses may be striking and easily seen from a ship's deck. It is to be noted that density may not change much across such a sharp line of demarcation because the more saline water is also much warmer.

A similar situation, though less extreme can be encountered at any time north of the Gulf Stream

between Cape Hatteras and the Grand Banks. Here the westerly winds sometimes drive the relatively fresh coastal waters far offshore. The situation southeastward from Montauk Point, Long Island, in July 1938 (Figure 5) affords a good example of relatively sharp salinity gradients near the surface caused by coastal water being carried more than 100 miles beyond the limits of the continental shelf. Although it is just such situations which make it desirable to compensate the submarine-model *bathythermograph* [BT] for salinity changes so that it will indicate the ballast changes correctly, from the acoustical standpoint the vertical variations in salinity shown in Figure 5 are negligible, for in each case the vertical salinity gradients are accompanied by relatively much stronger temperature changes. It is necessary to find a situation where shallow salinity gradients occur independently of temperature gradients before sound transmission is noticeably influenced. In the open ocean this very seldom occurs. However, since one of the major assumptions in maximum range predictions based on BT observations is that vertical salinity gradients can be neglected, it is advisable here to discuss this matter in more detail.

The refraction pattern might differ significantly from that indicated by a BT trace in the following possible circumstances:

1. A positive temperature gradient might be significantly reinforced by an increase of salinity with depth.

2. Within an isothermal surface layer salinity might increase with depth, causing increased upward refraction.

3. A slight negative temperature gradient might be partially or entirely offset by an increase of salinity with depth.

4. A negative temperature gradient might be reinforced by a decrease of salinity with depth.

6.3.1 Positive Salinity Gradient and Positive Temperature Gradient

During periods of rapid cooling, positive temperature gradients may be developed near the surface. Since this condition is thermally unstable it ordinarily occurs only to a slight degree and during calm weather.

Wherever a marked positive temperature gradient exists it is safe to say that there is also a positive salinity gradient which is at least sufficient to counterbalance the thermal instability of the water column. The combination of positive temperature and salinity gradients may occur when there is a heavy rain that freshens the surface layer, and when the rain is colder than the sea water or is followed by conditions that favor surface cooling by evaporation.

Still more marked examples are found near the edge of a current or along the continental slope where there is a flow of colder over warmer and more saline water. In such cases the density gradients are often so highly stable as to permit a submarine to balance on what would appear from the temperature trace alone to be an unstable layer.

6.3.2 Positive Salinity Gradient in Isothermal Layer

This situation can and does occur occasionally in the open ocean. It is relatively common close to the land in early spring. However, offshore the resulting increased upward refraction is seldom critical to sound conditions, nor is the resulting stability of the water column often sufficient to influence trim significantly in diving.

In the open ocean salinity can increase with depth within a virtually isothermal surface layer during and after a heavy rain, provided the winds are light and provided the temperature of the rain water is close to that of the surface water. The circumstances are probably most frequently favorable in the doldrum belt.

6.3.3 Positive Salinity Gradient and Negative Temperature Gradient

This situation could occur when slight surface warming is accompanied by precipitation.

In the current range-prediction method the minimum negative temperature gradient that is significant is a decrease of more than 0.3 degree between the surface and a depth of 30 feet. For the downward refraction thus produced to be counteracted, the positive salinity gradient would have to average more than 0.4 ‰ to 0.7 ‰ over the same depth range (see Figure 3, Chapter 3), depending on the surface temperature. It is unlikely that this ever occurs in the open ocean, except possibly in nearly calm weather when the negative temperature gradient persists for several days. Sufficient precipitation is not apt to take place during the few hours when slight negative tem-

perature gradients become established by diurnal warming.

6.3.4 Negative Salinity Gradient and Negative Temperature Gradient

A more likely case is that surface warming is accompanied by evaporation, the negative salinity gradient being insufficient to counteract the effect of the negative temperature in maintaining stability. In this case the downward refraction due to temperature would be reinforced slightly by the salinity gradient. It is believed that this effect is common in such specialized situations of dry, warm air as occur in parts of the Mediterranean, the Red Sea and the Persian Gulf. However, the further reduction in range which can occur in this way is of minor practical importance.

PART III

GEOGRAPHICAL AND LOCAL VARIABILITY

Chapter 7

OCEAN CURRENTS

THE factors considered up to this point are those for the most part which have an orderly and generally gradual effect on temperature and salinity structure. A picture has been presented of a more or less idealized ocean with a temperature structure which is permanent and relatively constant except near the surface where small-scale heating, cooling, and mixing processes result in diurnal and seasonal temperature changes.

However, it has gradually become apparent that there are important geographical variations in temperature structure which are caused partly by climatic variations and partly by the great ocean currents. Some knowledge of currents, both as to their general characteristics and the location of the major systems, is essential for mastery of the problems of subsurface warfare.

Variability of a more local nature must also be considered. Under this heading are included a wide variety of phenomena. The surface processes of heating and cooling are subject to a great deal of local variation, particularly in temperate and polar regions, where relatively sudden and violent weather changes are common. Various kinds of small-scale thermal structure are produced as a result of water transport or meteorological influences. Finally there are the special phenomena of coastal waters. All such variability not only is an essential part of oceanography but also plays an important role in sound transmission.

7.1 PRINCIPLES OF OCEAN CIRCULATION

7.1.1 Water Movements in Relation to Density Distribution

Previous sections have mentioned the movements of water that result from changes in density. In the tropics where surface heating is strong, the light water thus formed tends to spread northward and southward over the surface and to be replaced by colder water from below. As it moves into high latitudes, it overlies water that is colder but less saline, having been subjected to less heating and less evaporation. Thus when the tropical water cools, its salinity makes it denser than the water underneath, and it sinks. This surface transfer of water toward the poles is compensated by a return flow which largely takes place as a slow drift in the depths of the ocean. Similar movements also take place on a much smaller scale as a result of local heating and cooling.

In discussing the forces involved in such movements, it is convenient to compare them with meteorological phenomena, since the problems are essentially the same. A weather map shows isobars, lines of equal barometric pressure separating low- from high-pressure areas or topographic contours of an isobaric surface. In the sea as in the atmosphere, pressure increases downward because of the weight of the overlying layers, and the pressure at a particular depth will vary according to the density of the overlying medium. It is therefore possible to chart the pressure distribution in the sea (usually by plotting the topography of a selected isobaric surface) which will show the direction of water movement in the same way that the isobars on a weather map indicate wind direction. The usefulness of these topographic charts depends on the fact that the pressure gradient is zero in the direction parallel to the contours. Therefore, the initial tendency is for the water to flow at right angles to the contours, that is, downhill. As soon as the water is set in motion, however, it is deflected from its downhill course by the effect of the earth's rotation, as will be explained below. As long as the isobaric slope is maintained on a rotating earth, the current will run more or less parallel to the contours of the isobaric surface in the same way that the wind follows the isobars on a weather map. In order to understand this situation fully, it is necessary to examine in detail the effect of the earth's rotation, which will be taken up in the next section. It will also be necessary in dealing with water movements in general to discuss the important role played by wind-generated currents.

7.1.2 Coriolis Force

The effect of the earth's rotation on moving bodies is known as Coriolis force, after the French physicist

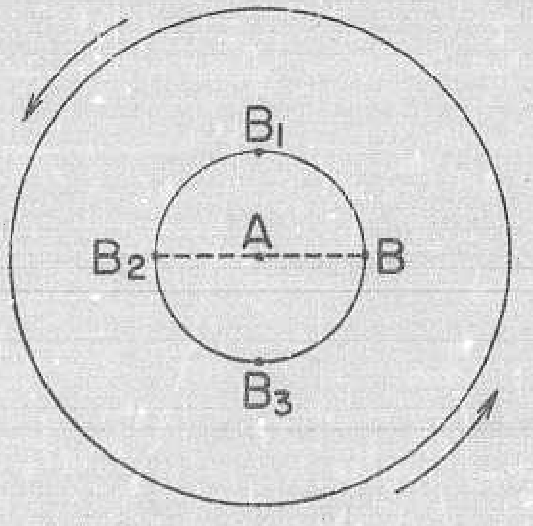


FIGURE 1. Diagram illustrating Coriolis force—rotation of points near the North Pole.

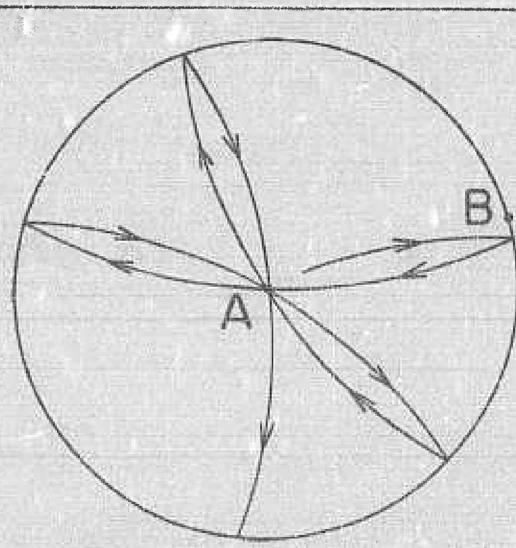


FIGURE 2. Diagram illustrating Coriolis force—apparent motion of a swinging pendulum on a rotating earth.

who evolved the mathematical theory. It is a fictitious force, as will be explained, and acts always at right angles to the direction of motion. Its effect is to make a current of fluid particles seem to be deflected toward the right in the Northern Hemisphere and to the left in the Southern Hemisphere. Only at the equator is Coriolis force nonexistent, and it increases to a maximum at the poles, varying as the sine of the latitude.

To explain how this force acts, suppose an observer is standing at the North Pole in the center of a horizontal circular platform and is looking at a point on the edge of the platform. In Figure 1 the position of the observer is at A, and he is looking at point B. The earth rotates in the direction indicated, and point B rotates with it, taking the successive positions B_1, B_2, B_3, and returning to the original position of B in 24 hours. The observer, of course, turns as the earth turns, continuing to face B, and is not aware that the position of the latter has changed. It would be apparent to him, however, that some such motion was taking place if he built an instrument that was capable of moving in straight lines across the platform without being affected by the earth's rotation. Such an instrument would be a pendulum suspended from a tower at A and swinging toward and away from B, as indicated by the dotted line in the figure. It would continue to swing in this plane, but B would rotate away from it until at position B_1 the pendulum would swing in a line at right angles to the direction of B_1 from A. To an outside observer it is obvious that the pendulum is swinging in a straight line, but to the observer at A it would look as if B stands still and the pendulum swings more and more to the right. If the pendulum moved slowly enough so that its course on each swing could be plotted, it would appear to be moving in a series of curves, each one bent slightly to the right of the direction of motion as in Figure 2. After several swings its direction as shown in the figure would be about at right angles to a line from A to B, and it would

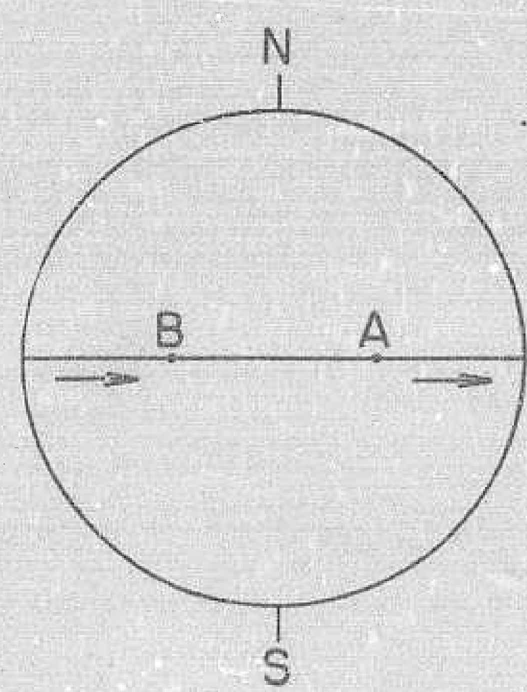


FIGURE 3. Diagram illustrating Coriolis force—rotation of points on the equator.

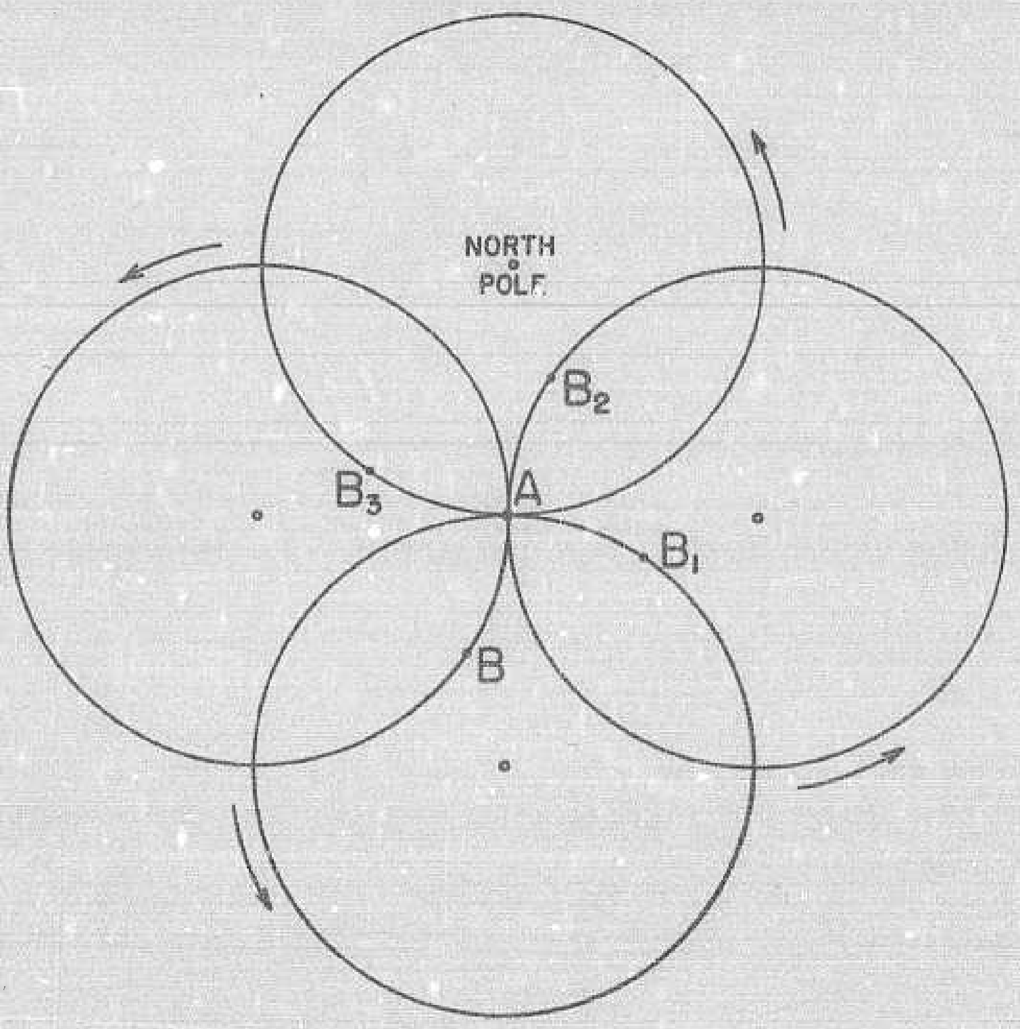


FIGURE 4. Diagram illustrating Coriolis force—rotation of points on the equator.

continue to change, making one complete apparent rotation in 24 hours.

A water mass at A or B will rotate with the earth and will therefore appear stationary to an observer at either spot. But if some force puts the water in motion in any horizontal direction it will behave similarly to the pendulum, that is, it will tend because of its momentum to move in a straight line so that the earth rotates under it and its path appears curved to an observer who is not aware of the earth's rotation. Thus a current with an initial impulse in the direction from A toward B will curve to the right and will pass to the westward of B.

In the same way a perfectly aimed bullet will strike to the right of the bull's-eye (in the Northern Hemisphere), whatever the direction between the gun and the target may be. While the bullet is in the air the earth has twisted under it slightly so that the initial bearing of the target in relation to space has changed. Thus any body which has been set in motion and is not acted upon by any lateral force appears, because of the earth's rotation, to be moving in a circular path, which is called its inertia circle. The radius of curvature depends on the velocity. The bullet appears to curve only slightly, but an ocean current with a much lower velocity has a smaller radius of curvature.

If point A were located at the South Pole, the earth's rotation would carry point B around it in a clockwise instead of counterclockwise rotation, hence the apparent deflection of a pendulum or of a current of water is to the left. This general rule for the direction of deflection holds for the lower latitudes as well as the higher; the deflection is to the right in the Northern Hemisphere and to the left in the Southern. The amount of deflection becomes less,

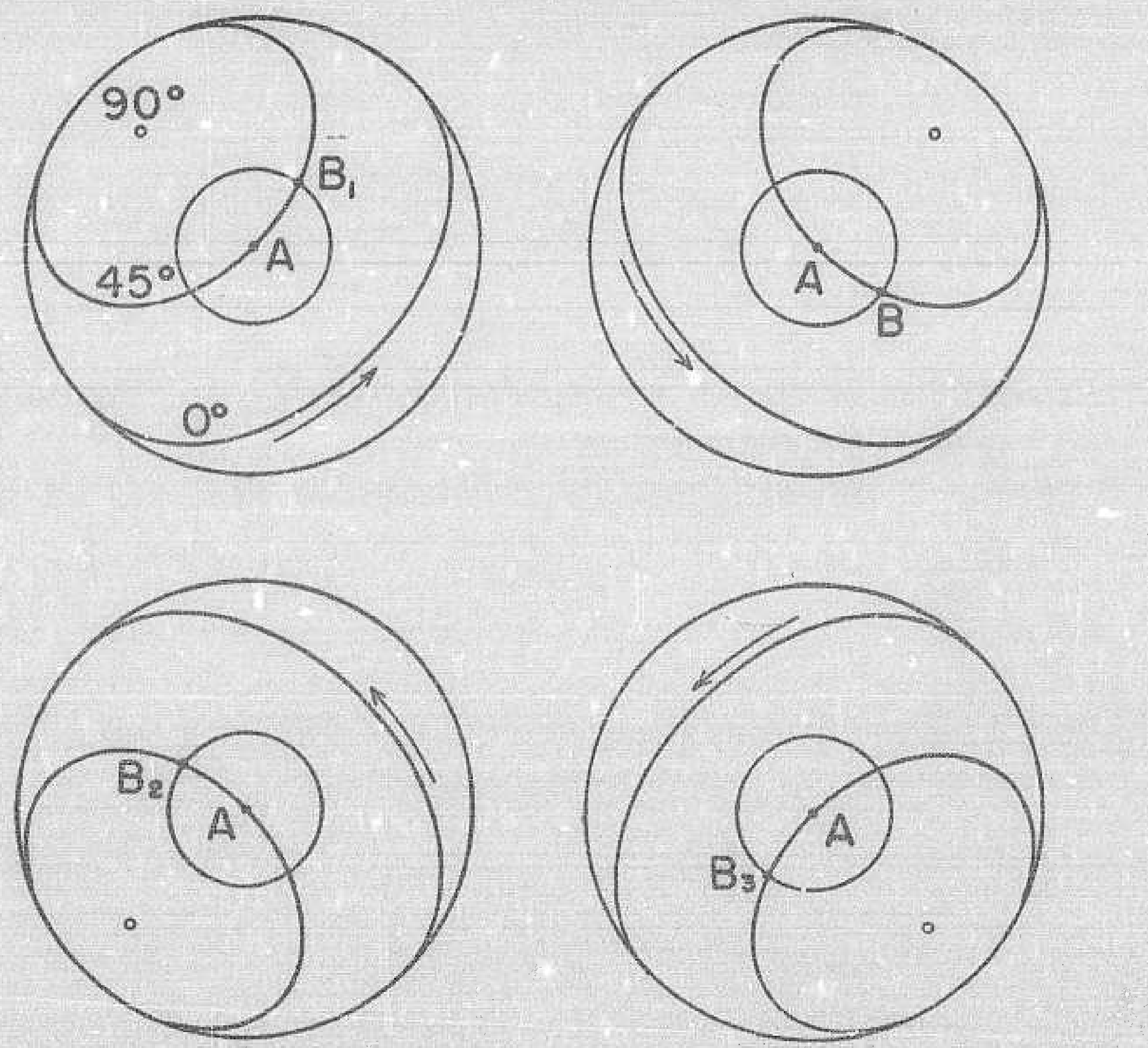


FIGURE 5. Diagram illustrating Coriolis force—rotation of points at 45° N.

however, at lower latitudes and ceases at the equator. Suppose points A and B are on the equator as in Figure 3. As the earth rotates, B follows A with no change in horizontal position. There is still a circling motion of a sort, which can be visualized by holding A in a fixed position and letting the whole earth rotate around it for a day's time as we look down on it from the North Pole (Figure 4). But to the observer at point A the circling motion is in a vertical plane, and it does not result in any horizontal deflections in the water around him.

If the points are located at an intermediate latitude, say 45° N, then the circling motion has some of the characteristics of both the polar and equatorial movements, in that it has both horizontal and vertical components. The resultant movement in a horizontal plane around the observer at 45° N is important. It is not quite so easy to visualize B circling around A at this latitude as it was at the Pole. In order to simplify the illustration, Figure 5 is drawn as if A is stationary and B is circling around it. Actually, of course, both points are in motion, circling around each other.

One of the most difficult things to understand about Coriolis force is the fact that although the earth rotates once every 24 hours, except at the North and South Poles it takes more than 24 hours for the points A and B to circle each other, and for this reason also, Figure 5 is an oversimplification of the facts. This was proven by Foucault, the physicist who first

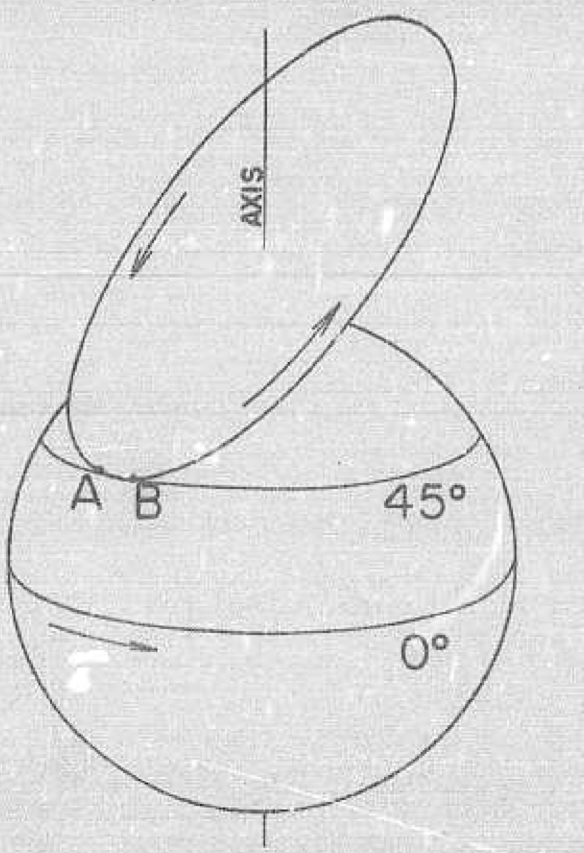


FIGURE 6. Diagram illustrating Coriolis force—rotation of points at 45° N.

demonstrated the pendulum experiment described above. Going back to that discussion, there was a circular platform at the Pole, rotating with the earth so that the pendulum was swinging above it in a straight line but apparently making a complete rotation in 24 hours. Suppose now the platform is enormously enlarged and tilted so that its edge reaches points A and B on latitude 45° N. It still must be horizontal at points A and B because we are interested only in horizontal deflections. It must rotate with the earth, so its center is the prolonged axis of the earth. Thus it is as shown in Figure 6. This disk then is the plane across which the pendulum swings. It rotates as the earth does with its edge touching at points A and B. But its circumference is greater than the distance around the earth at latitude 45°; therefore, it is similar to a reduction gear, with one revolution of the disk requiring more than a complete revolution of the earth. But points A and B circle each other as the disk circles and the plane of the pendulum shifts in the same way, both requiring longer than 24 hours to complete their rotation.[a] As the disk is further enlarged in order to extend to lower latitudes, the circling motion becomes slower. Finally at the equator it is impossible for a disk horizontal with the surface of the earth to have the axis pass through it. In other words, the length of the circumference of the disk is infinity and the circling motion is zero. The apparent deflection of the pendulum or of a current of water varies with the speed of rotation of the disk and its points A and B. Therefore Coriolis force is zero at the equator and maximum at the poles, and it can be proven mathematically that the variation is proportional to the sine of the latitude.

7.1.3 The Circulation Theory

It is apparent now that since any movement of water is affected by the earth's rotation, the simple explanation of circulation presented in the previous

[a] The length of time required for a complete rotation of the plane of the pendulum at any given latitude is called a *pendulum day*. The time required for a moving body at the same latitude to complete its inertia circle (see p. 61) is one-half of this time or *one-half pendulum day*. The reason for this may not be immediately apparent from the foregoing discussion. A somewhat more advanced treatment of the subject will be found at the beginning of Chapter XIII of reference 1, Chapter 1.

FIGURE 7. Diagram of water movements resulting from localized heating of the sea surface.

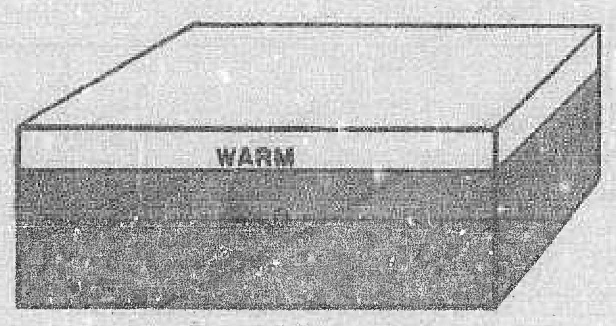


FIGURE 8. Equilibrium that results when movements shown in Figure 7 are carried to completion.

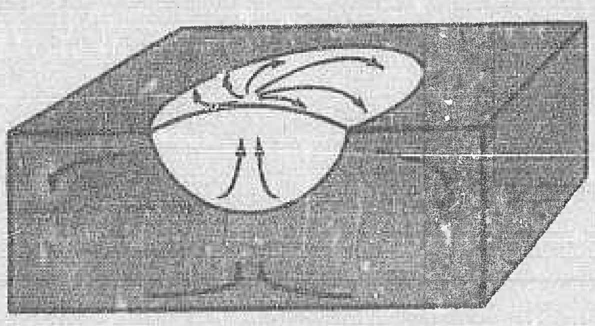


FIGURE 9. Effect of Coriolis force on water movements resulting from localized heating of the sea surface.

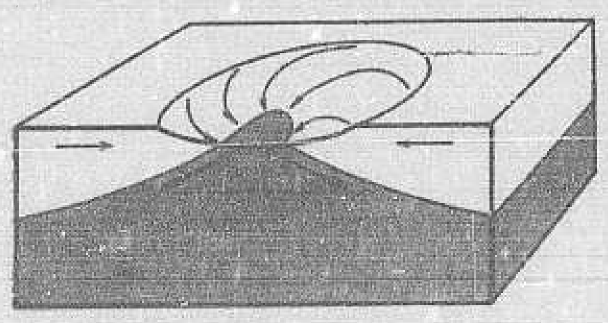


FIGURE 10. Diagram of water movements resulting from localized cooling of the sea surface.

section requires some modification. In building a theory that will explain the principles of circulation, it is desirable for the sake of simplicity to progress one step at a time, showing how each of these forces plays its part in setting up ocean currents. But in so doing it must be understood that each step is an ideal case that has, with minor exceptions, no counterpart in actual water movements which are affected by all the forces at once. At the end it will be seen that they fit together into a usable picture of the major current systems of the world.

First of all, Figures 7 and 8 show the effect of density changes on a nonrotating earth. The surface water in a particular area is heated until it is warmer than the water around and underneath it. Heating expands the water so that the surface of the sea is slightly elevated in the center of the warm spot, and immediately the water begins to flow downhill in all directions away from the center. Colder and denser water then presses up against the warmer and lighter water, buoying it up. Circulation therefore occurs as indicated by the arrows in the diagram, and it continues until there is an even distribution of density and pressure (Figure 8).

The effect of the earth's rotation is to cause all these movements to be deflected to the right (in the Northern Hemisphere). The result is a whorl of clockwise water movements spreading out from the warm center, as shown in Figure 9. Under ordinary circumstances this eddy of warm water can be expected to spread until the density differences are equalized and the condition of Figure 8 is established. The process is retarded, however, by the tendency of water particles to be deflected more and more to the right, so that at the edge of the eddy the movement follows very nearly a circular path.

The sinking of cold or saline water produces a somewhat similar current pattern but in the opposite direction. If the surface water in a particular area is cooled sufficiently to make it denser than the water underneath, it will sink until it reaches a level of its own density. As it does so the sea surface is depressed, and warm surface water flows in from all sides to take its place. Coriolis force transforms these movements into a counterclockwise whorl (in the Northern Hemisphere) as shown in Figure 10. At first glance these water movements appear to be deflected to the left rather than the right. That this is not so is demonstrated by Figure 11, which shows the movement of a particle of water from the edge of the warm water (A) to the cold center. At each instant of its progress, A, A_1, A_2, etc., the direction of force is toward the center as indicated by the dotted lines, while the direction of movement as modified by Coriolis force is to the right of the direction of pressure.

Suppose now the conditions of Figures 9 and 10 are combined in a continuous process. For example, the eddy of warm water is continually heated too rapidly for water movements away from the center to stabilize the density distribution completely. Then at a point on the periphery of the eddy the water is cooled just as rapidly as it was heated. Water will flow from the first point to the second, and it is conceivable that

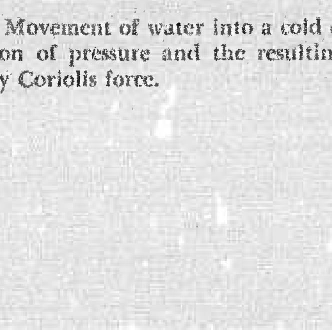


FIGURE 11. Movement of water into a cold center, showing direction of pressure and the resulting motion as modified by Coriolis force.

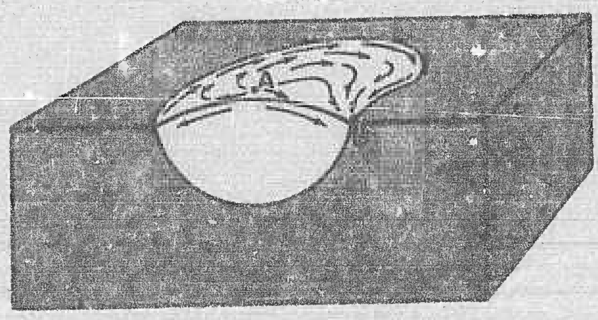


FIGURE 12. Movement of water between two localized areas, one of which is being warmed, the other cooled.

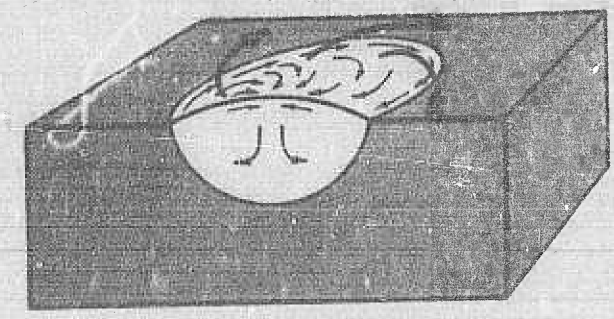


FIGURE 13. Diagram of a wind-driven eddy.

a permanent eddy of constant size and shape will be established; this is the result of a balance between the force produced by the density distribution and the frictional resistance of the water to this force. This situation can be visualized diagrammatically in Figure 12, in which point A is the center of heating, and the warm water is cooled at point B. The water spreads out from A in all directions in the form of a clockwise whorl as previously described and then converges at B. As long as the rates of heating and cooling remain constant the pattern of currents and the size of the eddy will also be constant. This condition of equilibrium is commonly known as a *steady state*. In parts of the eddy the density distribution is in a permanently unstable condition, particularly near the edge where there is a sharp downward slope in the thermocline. In other words the inequality in density structure still generates pressure which is directed outward from the center of the eddy in all directions. However, the water movements that must be produced as a result of the pressure gradient do not increase the size of the eddy; instead they take a circular clockwise course at its periphery. This is the extreme example of the application of Coriolis force. Just as Coriolis force is proportional to the mass and velocity of the movement of water and at right angles to it, so it exactly balances the pressure that produces the water movements and is at right angles to the direction of pressure. Thus, when the presence of a permanent slope in the density surfaces indicates that a steady state has been attained, the current that is generated is always at right angles to the direction of pressure, so that if an observer in the Northern Hemisphere faces in the direction in which a current is flowing, the density surfaces slope downward toward the right.

This balance between the pressure gradient and Coriolis force can perhaps be more easily understood by recalling the inertia circle described in the preceding section. It was stated that a particle in motion and not under the influence of any lateral force appears to take a curved path because the earth is turning beneath it. The radius of the circle varies with the velocity and the sine of the latitude. For a current of average velocity located in mid-latitudes this radius is about 15 miles. But the major ocean currents obviously have a very much larger radius of curvature, which means that they must be under the influence of a lateral force which deflects them from the path of the inertia circle. In other words, for water to flow in a reasonably straight path in the geographical sense, it must be acted upon by a component of gravitational force (the crosscurrent pressure gradient) which deflects it to the left in the Northern Hemisphere and to the right in the Southern just enough to balance Coriolis force.

In a very general way the description thus far developed can be applied to ocean circulation. Weak density gradients extending over great horizontal distances are important in transporting warm tropical and subtropical water to polar regions. Within the major ocean currents where steady-state conditions are approximated at least through parts of their courses, the flow is very nearly at right angles to the pressure gradient. However, the uneven nature of the processes that originate the currents leads to continual variations in velocity and varying amounts of crosscurrent transfer which shifts their position. Near the surface the effect of pressure gradients is also greatly modified by the wind systems of the earth. Around each of the central basins of the oceans the winds form a great anticyclonic eddy, consisting primarily of the trades and prevailing westerlies. The force of these winds produces similar eddies in the ocean, the general features of which are illustrated in Figure 13.

Movement of water in these eddies is deflected by the earth's rotation to the right of the wind direction, hence there is a drift of water toward the center of the eddy accompanied by a slight elevation of the sea surface where the water is converging. This creates an unstable pressure distribution that is compensated in two ways: (1) by a return drift toward the periphery of the eddy in the water underneath the wind-driven surface layer, and (2) by a general redistribution of density structure to equalize the vertical pressure. In other words there is a tendency for readjustment of density surfaces so that the pressure on the underlying deep water caused by the weight of water above it is uniform, and any tendency to increased weight due to elevation of the sea surface is offset by an increase in depth of the relatively light mixed layer. Thus the light water accumulates in the center of such a convergence, and the density surfaces slope down toward the center from all sides, giving rise to a permanent lens-shaped body of warm water.

This situation is stable only insofar as it is maintained by the force of the wind. If the latter ceased, the warm water would spread out in an even layer over the surface in the same manner as described in Figures 7 and 8. In this respect it is similar to an eddy of warm water maintained by surface heating, which, as has been seen, is permanent only by the action of an external agency.

The similarity does not end there, however. In each case there is an elevation of the sea surface and deformation of density surfaces, resulting in the development of a pressure gradient which in turn produces a current flowing at right angles to it. All these factors are interrelated—the difference in density between the warm water above and the colder water below, the slope of the thermocline (as influenced by latitude), and the velocity of the current produced. The relationship can be expressed by a mathematical formula, so that by measuring the vertical density structure of ocean waters, it is possible to determine the direction and velocity of currents. Current systems are commonly studied in this way, for actual measurements of the currents are very inaccurate unless the vessel is equipped for anchoring in deep water, and even so they are difficult and laborious. The principle of determining ocean currents from the density structure of the sea, which is generally known as the Bjerknes Circulation Theory, is one of the most important contributions to modern oceanography.

But as indicated above, while the mathematical relations of currents with the density structure of the water are always about the same, the causal relationships are often inextricably mixed. The wind may set up a current, and the transport that results will cause the density surfaces to slope. Contrariwise, density slopes that result from heating or cooling processes will cause a current to be formed. Often both processes are involved, and some of the most powerful ocean currents are those in which the prevailing winds and the density distribution work together.

7.1.4 Wind Transport

In the open ocean many of the permanent currents move in roughly the same direction as the prevailing winds and are primarily wind-driven. It is obvious that these currents are deep and powerful and that huge amounts of momentum are involved. But such basic questions as how long a wind must blow before a current becomes established and in what direction this current will flow still must be dealt with largely on the basis of theory, for few satisfactory field studies have been made.

The classical theory of wind currents was advanced largely on the basis of mathematical calculations, and although it has since been refined and modified, it is best to begin by discussing it in its simple form. The theory assumes a limitless, deep ocean in which there is no change in density with depth. The force of the wind sets up a drift current in the surface water. As soon as the water is set in motion it is acted upon by Coriolis force, and when steady-state conditions are reached the resultant current at the surface is 45 degrees to the right of the downwind direction in the Northern Hemisphere and to the left in the Southern. The water below the surface is dragged along by friction, the velocity decreasing with increasing depth, and the direction of motion swinging more and more to the right. This is the so-called Ekman spiral (Figure 14), named after the author of the theory. If the degree of frictional drag, or so-called eddy viscosity, is constant with depth as assumed in the calculations, then it can be shown mathematically that the net transport of the wind-driven surface layer will be 90 degrees to the right of the wind (in the Northern Hemisphere). It is believed that this sort of motion will become established within about 12 hours of the onset of a steady wind. Earlier the flow will be more nearly in a downwind direction.

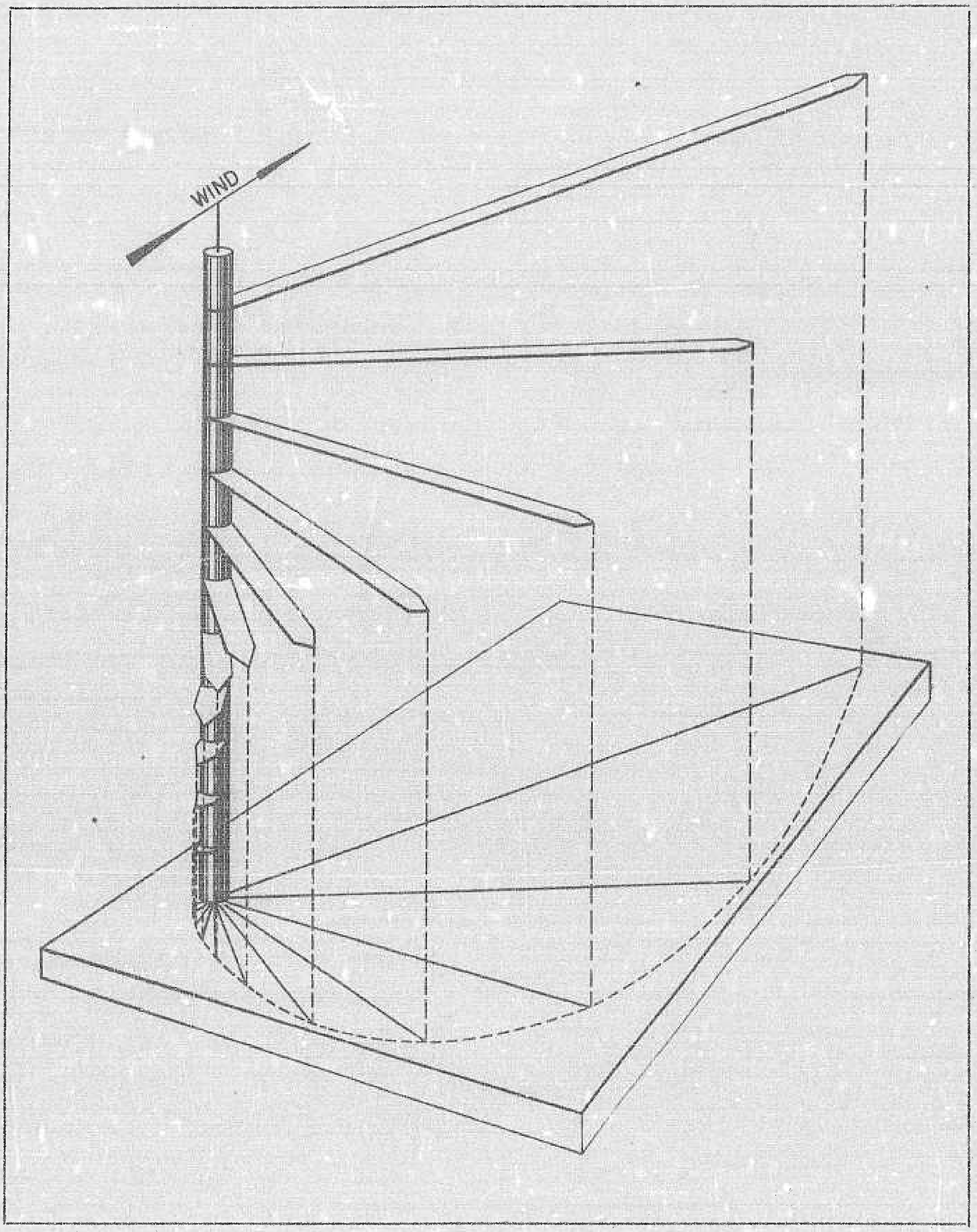


FIGURE 14. Diagram illustrating the Ekman spiral.

This situation is complicated by the fact that wind transport is always accompanied by wave transport. Furthermore it is associated with a considerable amount of vertical turbulence, frequently with the formation of convection cells of the kind described in Section 5.2.1, which produce some mixing to the bottom of the isothermal layer. Moreover, it has been observed that in the convergences of convection cells the surface water moves downwind at a considerably more rapid rate than in the divergences. This can sometimes be seen on a cold day by observing the bubbles and foam on the sea surface. Since the flow of water in response to the wind is uneven and since mass vertical motions occur in the convective layer, it is clear that the mathematical assumptions oversimplified the actual movements of water in the wind-driven surface layer.

Furthermore, when water is transported by the wind, other water tends to take its place (compensating currents), while ahead of the current, wat[illegible]nds to be pushed forward and piled up, leading to a slight elevation of the sea surface and a depression of the thermocline to the right of the wind. This causes the development of a deeper current, commonly known as a gradient current, according to the principles of the circulation theory, which flows at mid-depths parallel to the wind direction and below the Ekman spiral. When compensating and gradient currents have been set up, they seriously affect the direction of the original wind-driven current, and the wind-drift theory in its simplest form is no longer completely correct. Thus it is argued that when a steady state has been reached, the deflection of the surface water from the downwind direction will be reduced by perhaps half the 45 degrees called for by the simple theory, and indeed in the trade wind belts, at least, it is possible to demonstrate that the current at the surface is at an angle of roughly 15 to 20 degrees to the right of the wind.

For the present purposes, however, what is particularly important to subsurface warfare is not so much the question of the exact direction of flow or velocity, but rather a general understanding of the way in which local variability of the winds can transport the surface water and sometimes carry warmer water over colder and vice versa, thus radically affecting sound conditions. Moreover, wind transport and the associated gradient currents may in some cases move considerable masses of the warm surface layer, piling it up and thickening the isothermal layer (convergence) or spreading it out and reducing the amount of mixed water (divergence).

The effects in the open ocean of convergence and divergence on a large scale are evident on the summer-season sonar charts (see Figures 9 and 10 in Chapter 5). In the latitude of westerly winds, for example, the sound conditions are generally better on the lee side of the ocean than on the windward. Likewise, in the trade wind belt sound conditions in the west are relatively good, for example in the Caribbean.

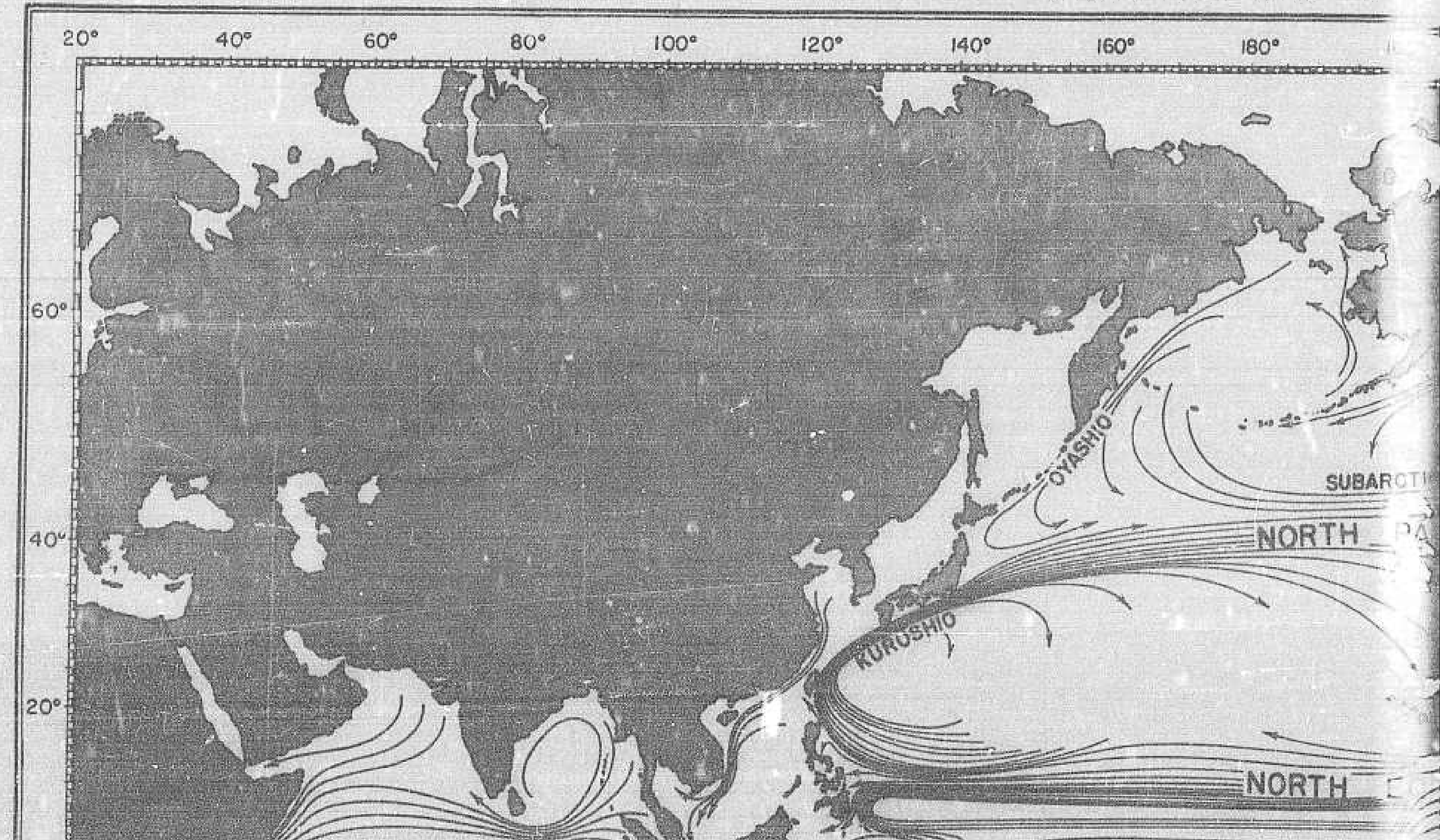
7.2 MAJOR CURRENT SYSTEMS OF THE EARTH

Figure 15 is a chart of the major surface currents of the oceans. For the most part their position shifts only slightly with the seasons, although in the northern part of the Indian Ocean and along the China coast the direction of their flow is actually reversed. Here they are shown in their midwinter position.

If Figure 15 is compared with previously published current charts a marked difference will be noted. Most current charts show the average direction and strength of all available drift measurements for each small area of the ocean, usually supplemented by inferences from the more numerous wind observations. As a result they make the currents appear broad and diffuse and closely dependent on prevailing local winds. It is not always easy from such a chart to distinguish clearly between the central portions of the major eddies, where the direction of drift is relatively haphazard, and the edges of those eddies where one finds true currents involving significant transport in a nearly constant direction and enough momentum to leave them unchanged by occasional periods of opposing winds.

An attempt has been made in Figure 15 to show by the continuous lines where the direction of flow is most persistent, and to group these lines into bands outlining the edges of eddy movement in order to indicate where the currents are most clearly defined. The spacing of the lines cannot, however, be taken as an exact measure either of constancy or of speed, and it should be noted that the Mercator projection makes them appear widely separated in the West Wind Drift, which is actually a fairly strong current.

The courses and speeds of the currents at the surface are well known through ships' observations, and oceanographers have studied the flow at greater


20°
40°
60°
80°
100°
120°
140°
160°
180°
60°
40°
20°
0°
20°
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60°
OYASHIO
NORTH
KUROSHIO
NORTH
NORTH EQUATORIAL
COUNTERCURRENT
SOUTH EQUATORIAL
W. AUSTRALIA
EAST AUSTRALIA
AGULHAS
WEST WIND DRIFT
1

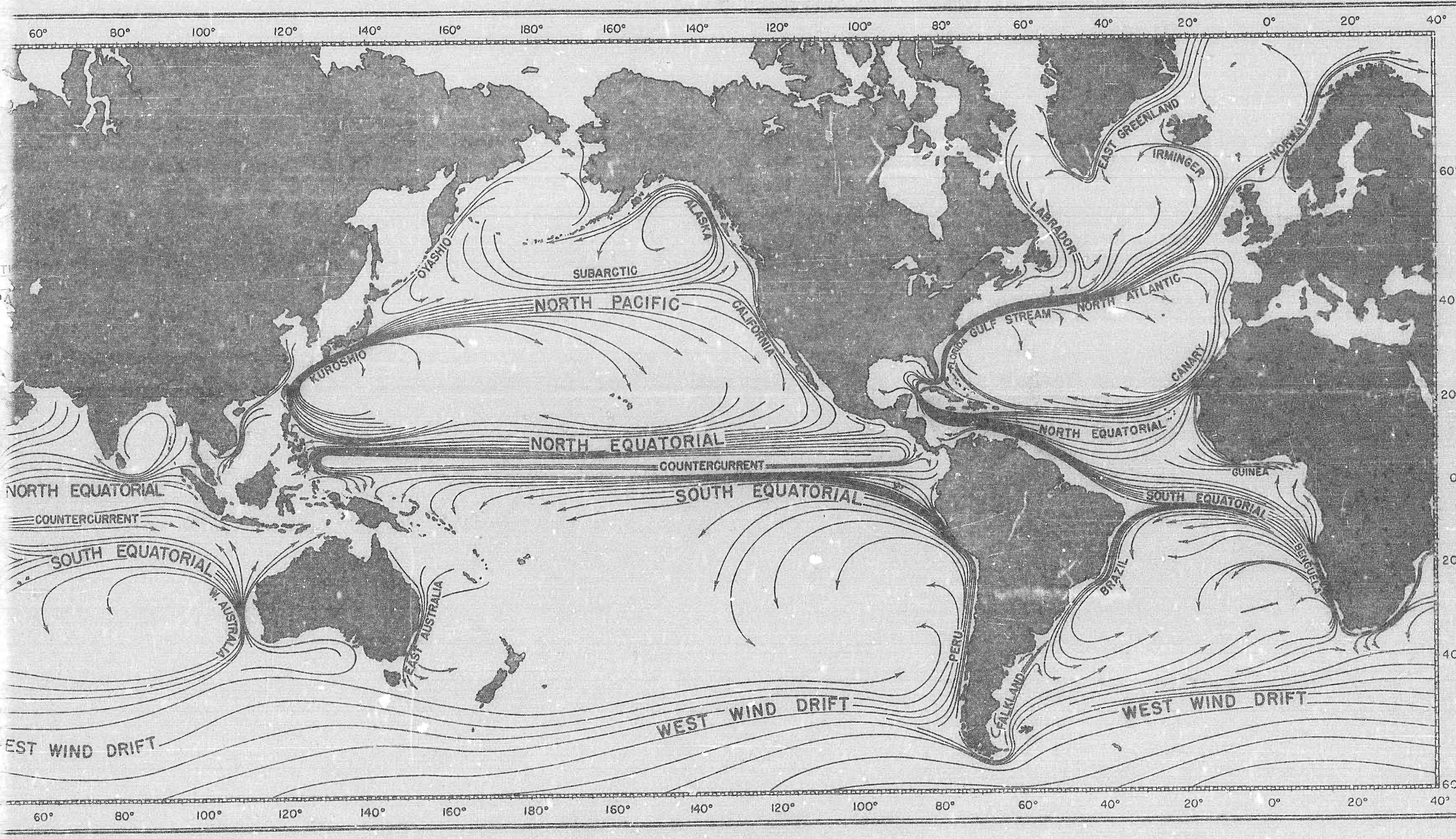

FIGURE 15. World chart showing the major surface currents.

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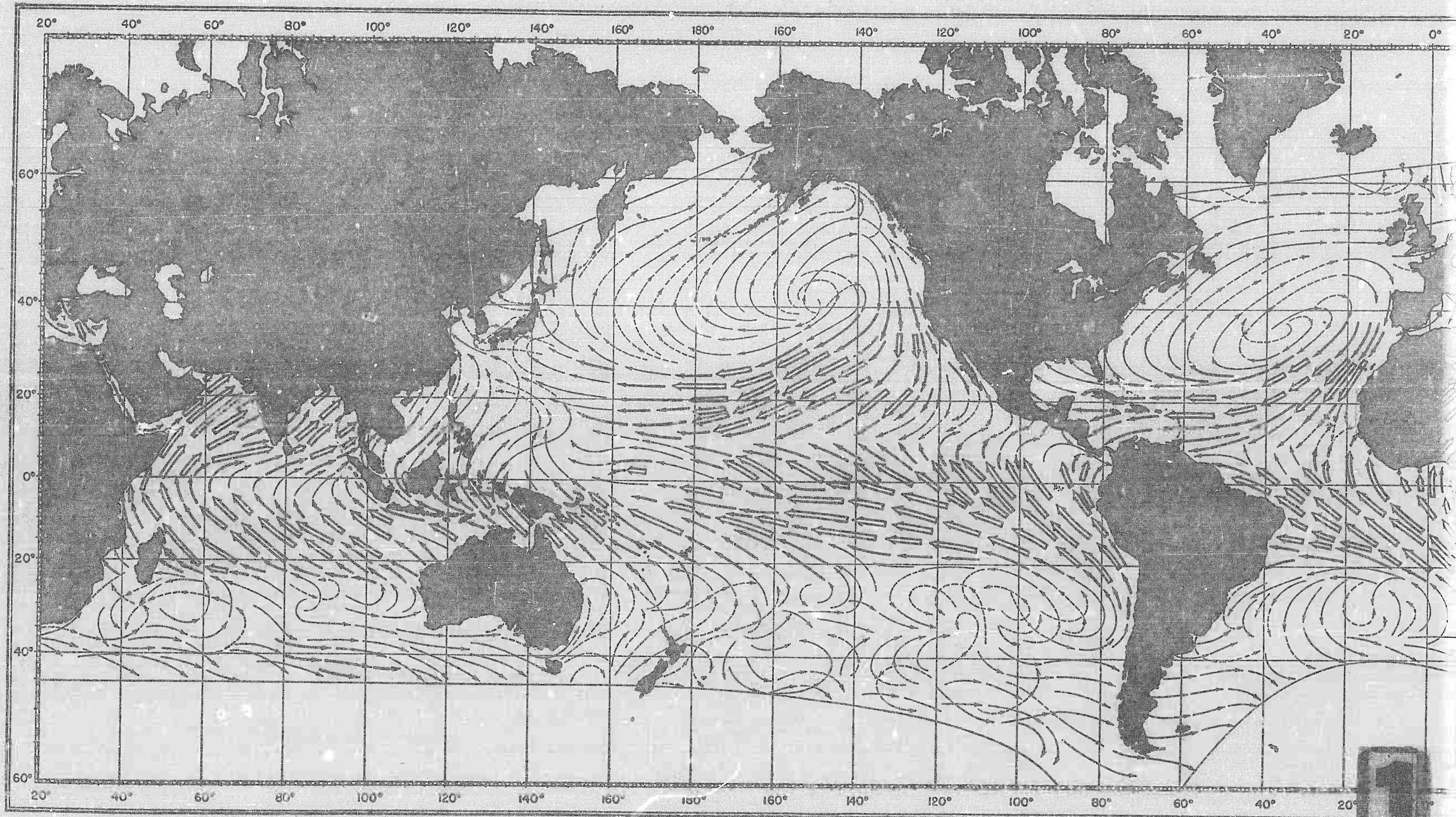

FIGURE 16. World chart showing the prevailing winds in February.

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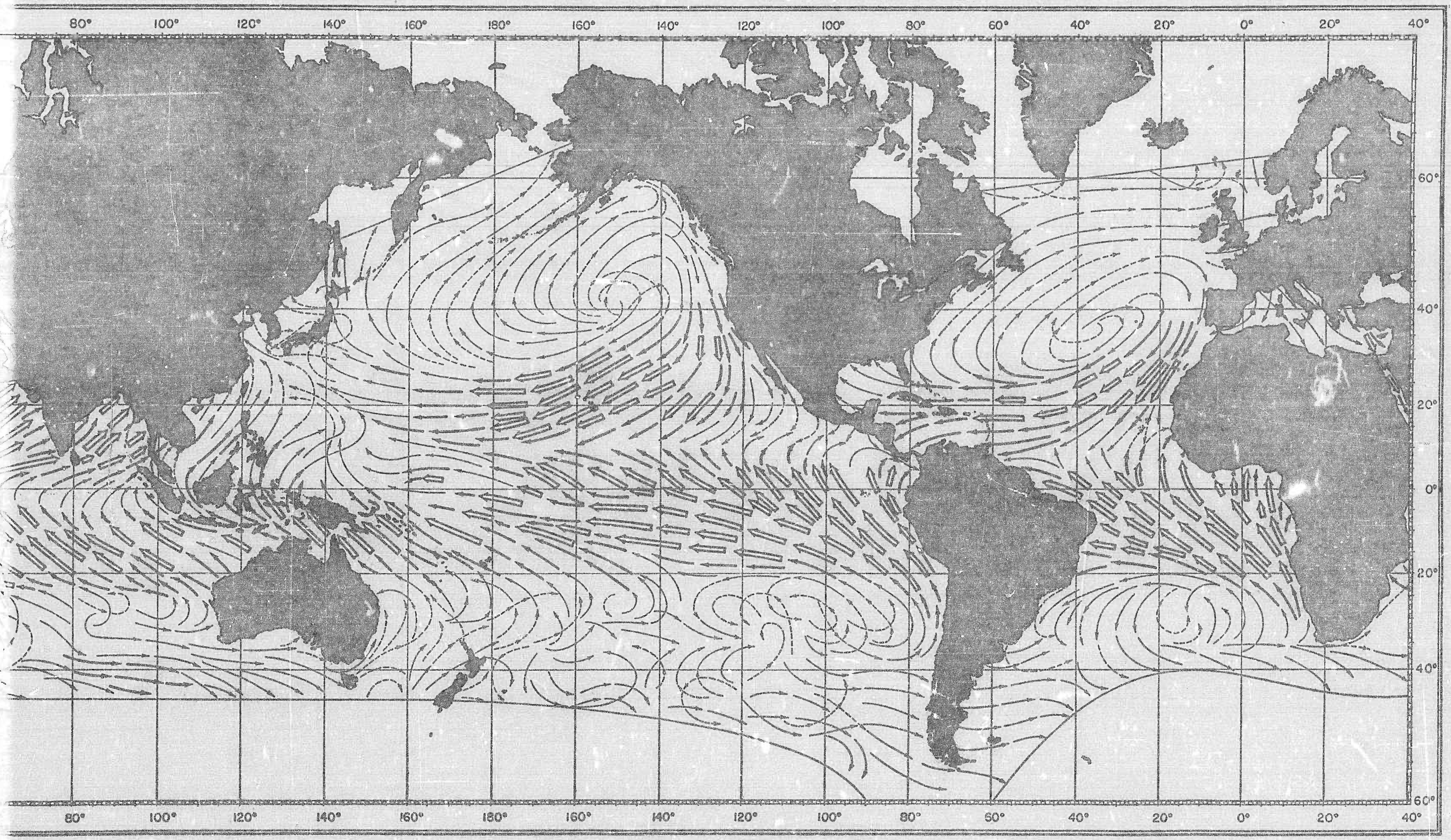

FIGURE 16. World chart showing the prevailing winds in February.

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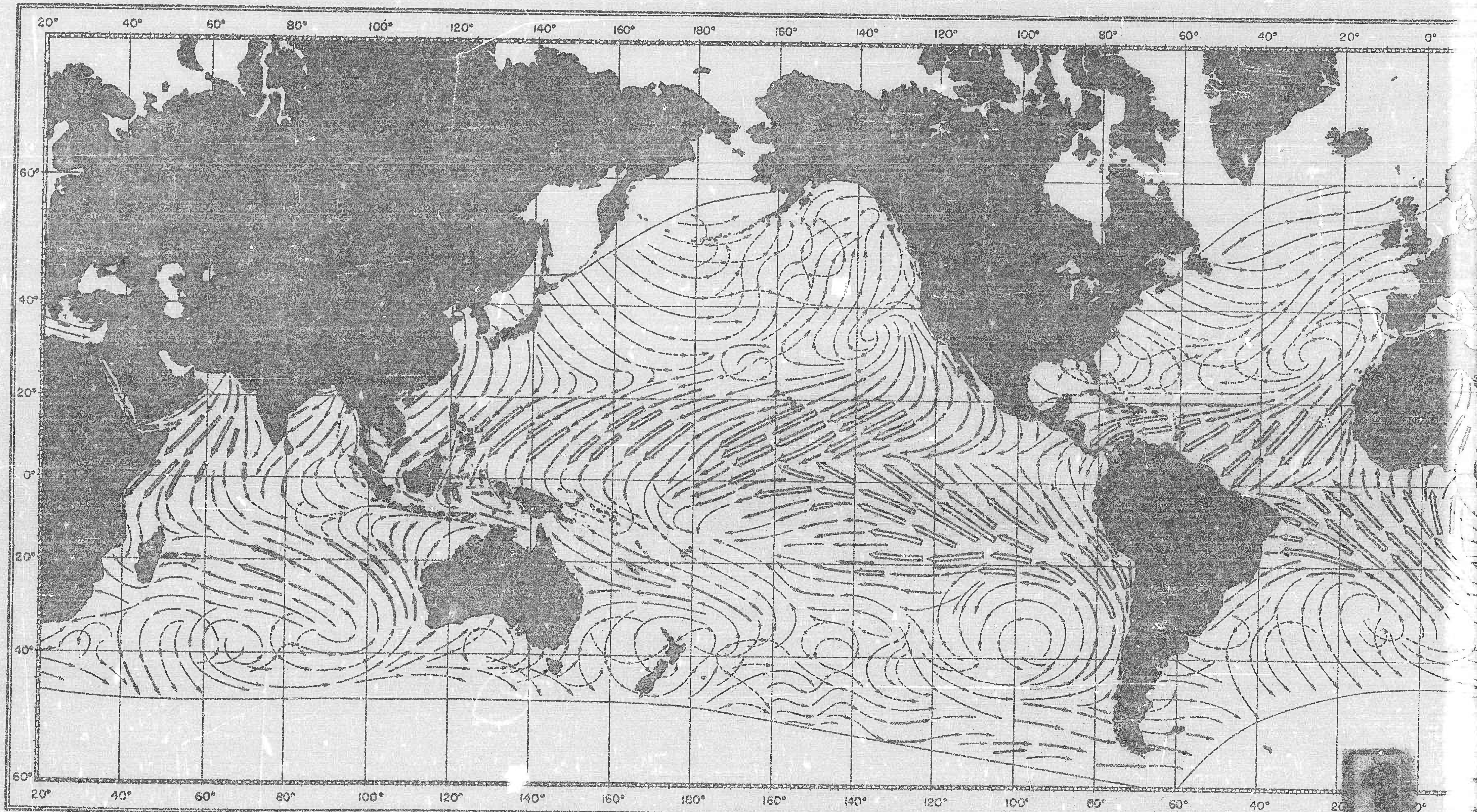

FIGURE 17. World chart showing the prevailing winds in August.

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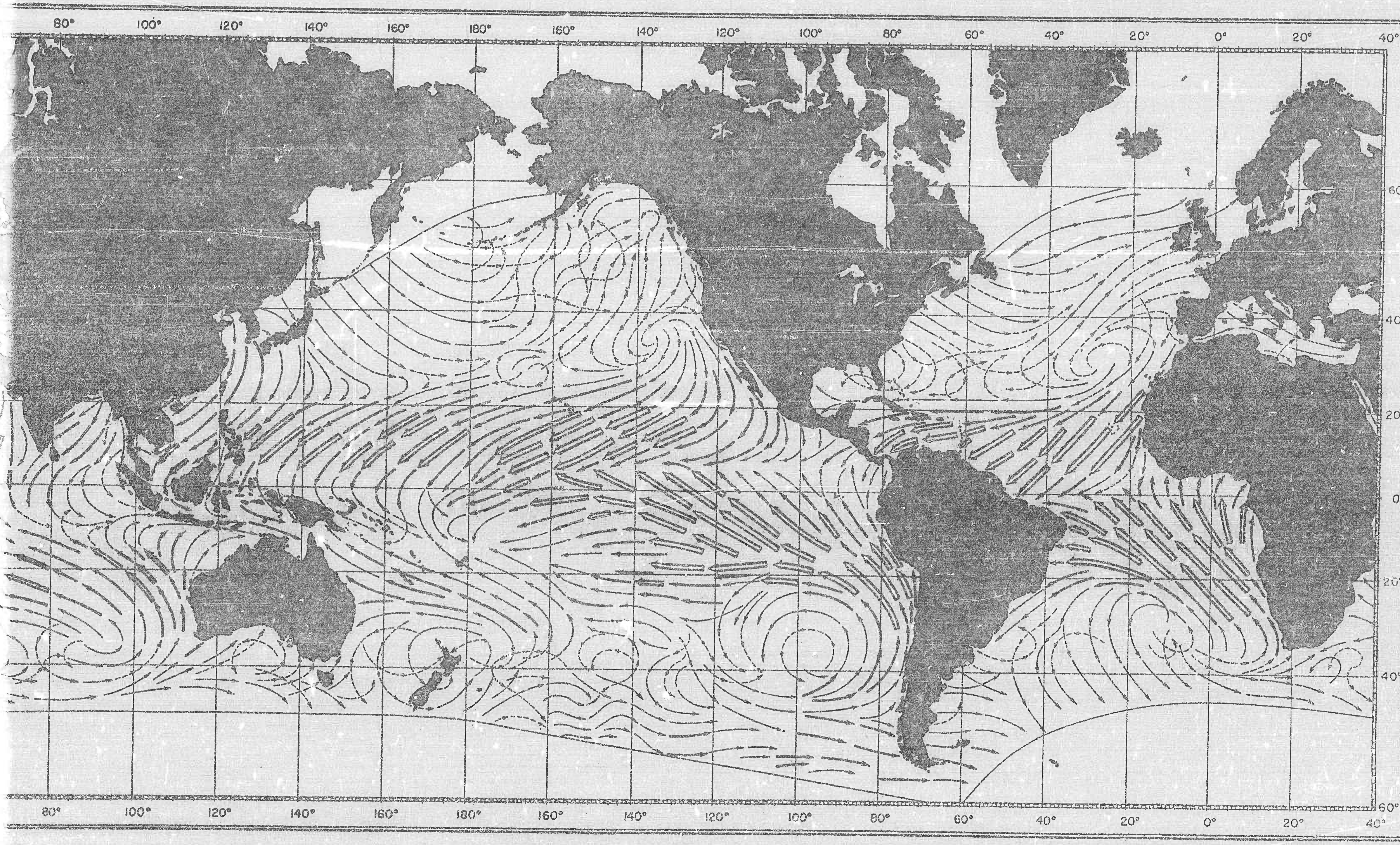

FIGURE 17. World chart showing the prevailing winds in August.

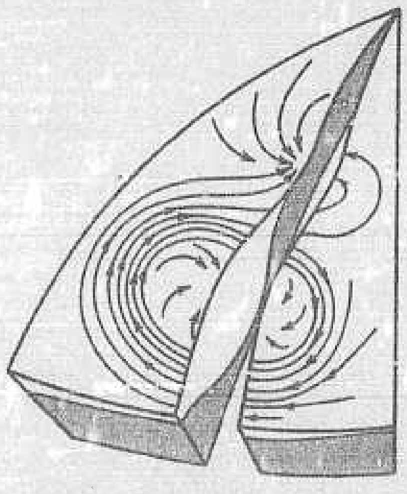

FIGURE 18. Diagram of typical ocean circulation, wind-driven eddy and subpolar convergence.

depths, partly by direct observation and to a larger extent by determinations of the density structure. The velocity of the currents is greatest near the surface where in a few places they reach a speed of 3 or 4 knots. The greatest depth at which a significant amount of flow can be detected varies with each current and in different parts of the same current, but in some cases this depth is greater than a mile. It is apparent therefore that the larger currents carry huge volumes of water. For example, the total transport of the Gulf Stream in the latitude of Chesapeake Bay is approximately 100 million tons a second.

In examining the currents it is worth while to compare them with the wind systems of the world (Figures 16 and 17), which are similar in many respects and are to a large degree responsible for the general pattern of the currents. This is particularly true of the west wind drift in the Antarctic and of the North and South Equatorial Currents which lie in the trade wind belts. The latter currents form part of the great eddies centering in mid-latitudes, clockwise in the Northern Hemisphere, and counterclockwise in the Southern, corresponding to the prevailing wind direction. Since they are primarily wind-driven, they are swiftest at the surface. In the main thermocline and the upper part of the deep water layer, horizontal eddy-type of motion gradually decreases with depth, giving way to slower deep water transport.

These eddies take the general form described in the preceding section, and together with sinking centers in higher latitudes they set the dominant pattern of the current systems of each ocean basin. Figure 18 is a diagrammatic representation of the scheme of circulation, showing the density structure and the direction of the currents in a combined wind-driven eddy and sinking center.

It is important to consider the density structure of the oceans in relation to the currents, since it is not only essential for proper understanding of the subject but also has practical implications from the standpoint of echo ranging. For this purpose reference is made to previous figures (9 and 10, Chapter 5) which showed layer depth contours taken from the sonar charts for December to February and June to August. These are in a sense a superficial picture of the density distribution of the sea, but they are adequate for the present purposes. Winter conditions (Figure 9, Northern Hemisphere; Figure 10, Southern) are particularly useful for examining the density structure in relation to currents.

In the eddy currents centering in mid-latitudes, the density surfaces slope downward toward the right in the Northern Hemisphere and the left in the Southern as is expected according to theory. Thus in the center of the eddies, layer depths are greater than around the outer edges of the currents, and the winter sound ranges are correspondingly better. On the edges of the currents the warm water is often found as a shallow wedge over colder and less saline water. This condition is further shown by bathythermograms of the Florida Current and of the Gulf Stream further north (Figures 19 and 20). The negative temperature gradients at the edge of the current make echo ranging conditions poorer than they are either in the main body of the current to the right or in the colder slope water, as it is called, to the left. With northerly or westerly winds the slope water is forced to overlie the warmer and more saline Gulf Stream water disrupting the normal temperature structure, producing temporary positive gradients, and setting up eddies that lead to complex and variable temperature conditions. For all these reasons the edges of such a current are poor and variable from the antisubmarine standpoint.

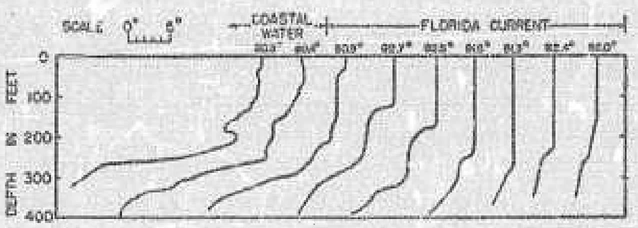

FIGURE 19. Series of bathythermograms across the Florida Current.

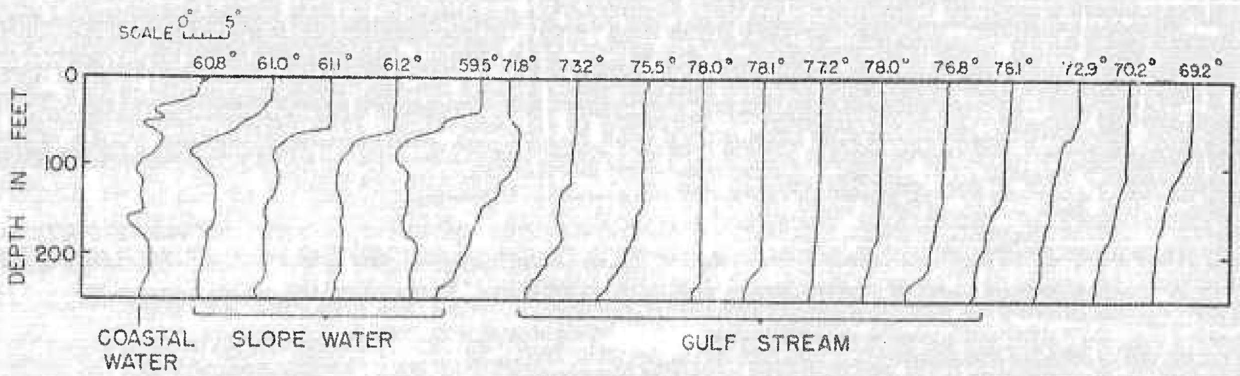

Figure 20. Series of bathythermograms across the Gulf Stream.

In summer (Southern Hemisphere, Figure 9; Northern, Figure 10 of Chapter 5) the development of the seasonal thermoclines obscures this general picture of density structure in the central basins, as shown in the sonar charts. The current systems and their relationship to the main thermocline are approximately the same, but they do not benefit sound ranging conditions in the center of the great eddies. There, as well as in the waters beyond the edge of the currents, seasonal warming shortens sound ranges. Where the current is strongest, the turbulence developed aids the vertical distribution of heat, hence the best sound ranging conditions in the summer are found in areas where there are currents. This is particularly true of currents that are partly or largely wind-driven so that the effects of wind-generated turbulence and turbulent flow are combined. However, sonar conditions are also good in such places as the Florida Straits where the wind is light and variable in summer and does not affect the current appreciably.

Within the North and South Equatorial Currents the density surfaces slope down toward the north in the Northern Hemisphere and to the south in the Southern Hemisphere (Figure 21), and water is transported not only westward but also away from the equator on both sides. Therefore where these currents border on the equatorial doldrum belt the thermocline is shallow, and hence echo ranging conditions are relatively poor in the doldrums. At the same time the steady blowing of the trade winds exerts enough stress on the sea surface to raise the sea level slightly (in the Atlantic ocean it is about 2½ inches per thousand miles) in a westward direction along the equator. The equatorial countercurrents found in the doldrums result as a downslope flow in the zone where the winds maintaining the slope are absent.

In the subarctic regions of both the Atlantic and the Pacific oceans, the dominant feature is a group of counterclockwise currents set up around the so-called sinking centers. The depression of the density surfaces and the thickening of the mixed layer that accompany these convergences make sound ranging conditions good except when strong winds interfere, or when lateral eddies between water masses of different temperature and salinity produce confused negative and positive gradients.

In the Southern Hemisphere, sinking of surface water derived from the tropics also occurs, but because of the strong circumpolar currents which are caused by the prevailing westerly winds and are unimpeded by the presence of land masses as in the Arctic, sinking occurs in a more or less continuous band at a latitude of about 50 to 60° S, rather than in localized centers. From this convergence southward, layer depths are almost invariably great enough for good echo ranging, but the effective sound range is frequently reduced by strong winds.

The actual differences in density in the convergences are generally slight, and while presumably a certain amount of sinking of heavier water occurs all the time in one part of the area or another, it seems probable that it is a highly variable phenomenon, much influenced by local water movements and weather. Ordinarily sinking occurs at the boundary between two water masses of slightly different temperature and salinity. Pronounced downward movement of water is favored by a wind that transports heavy water over a mass of lighter water, or by cold, calm weather that permits considerable masses of unstable water to develop at the surface before they begin to sink.

No measurements have been made of the downward currents that result, and there is only the

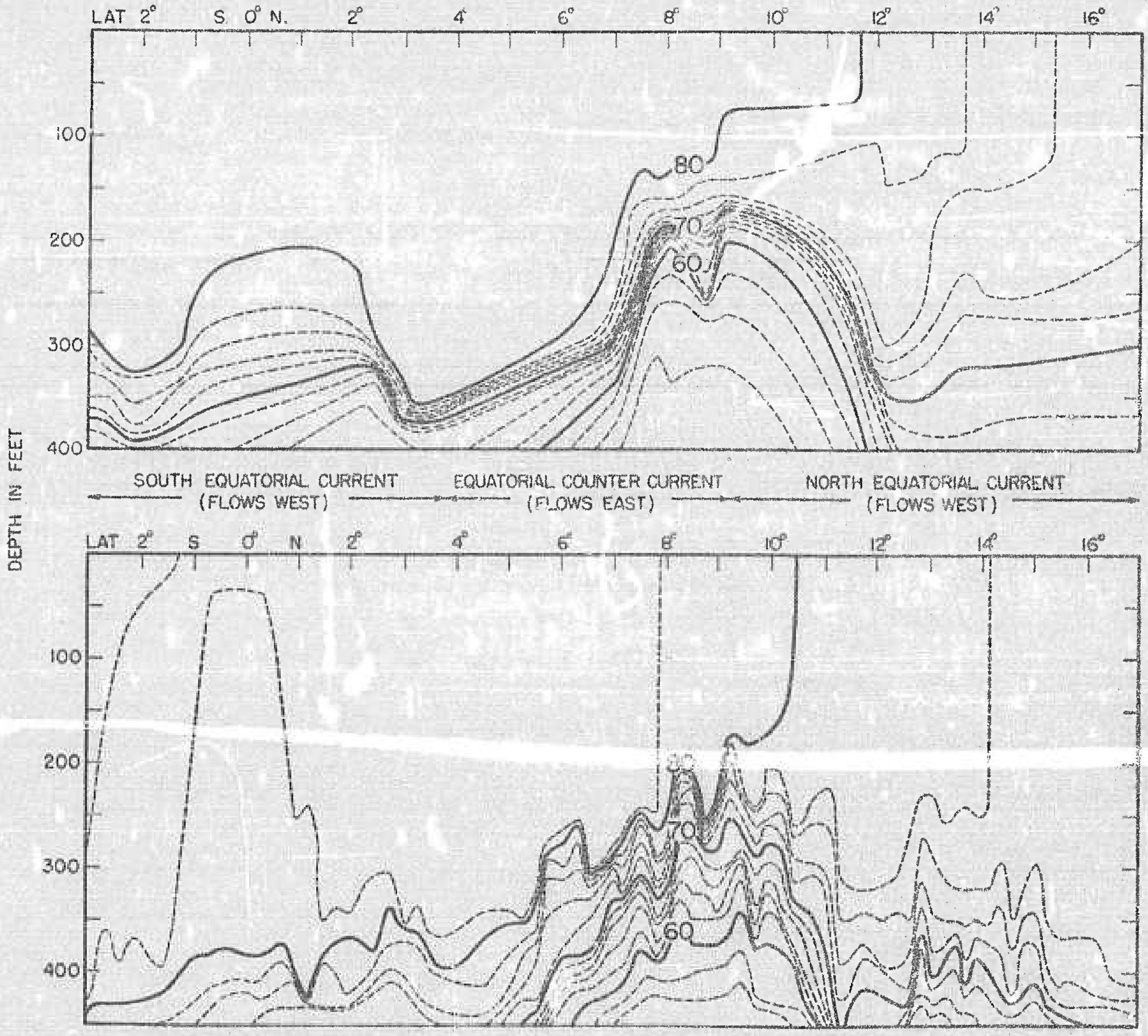

FIGURE 21. Profiles showing isotherms across the Equatorial Currents in the Pacific.

vaguest information about their size and form, but evidence of their existence has been observed from surface vessels. Sinking ordinarily occurs in a band a few yards wide and perhaps as much as several miles long. It has the choppy appearance of a tide rip and may be full of seaweed and other debris brought into it by the converging surface currents. The downdraft is strong enough to carry down debris of slight buoyancy, and the surface currents may be strong enough to hold a drifting vessel in the convergence in spite of a crosswind.

Such convergences are probably important from the standpoint of diving operations. Submariners use the term *fresh pocket* for a place where the vessel suddenly and for no obvious reason begins to sink and requires reballasting. This can happen any time when a submarine goes too near the lower limit of a supporting density gradient. Varying thickness and amount of temperature change in the thermocline is no doubt responsible for some of the instances reported. On the other hand, sometimes the submarine sinks very rapidly and checks its descent with great difficulty and at a dangerous depth. In such a case it may have encountered a convergence in which not only is there no increase in density with depth, but also there is a downward current of water comparable to downdrafts in the air that cause airplanes to lose altitude. From what is known about the shape of these convergences, it seems likely that a submarine held in one for any length of time has come into it on a nearly parallel course and should therefore change course about 90 degrees to escape.

Chapter 8

LOCAL VARIABILITY

8.1 WINDS AND WAVES

The great permanent wind-driven currents occur only in those parts of the oceans where winds blow fairly constantly in one direction. Local variations, particularly in latitudes where there is a succession of low- and high-pressure areas with constantly shifting winds, do not lead to pronounced transport. When, as frequently happens, permanent currents traverse such areas, it is only by virtue of their hydraulic head.

Local winds do not appear to be very effective in producing convergences and divergences, even on a small scale. In the open ocean the pattern of winds around a moving low-pressure area would, in theory, cause divergence, that is, a lessening of the thickness of the warm surface layer near the center of the wind system. On the other hand, as a low-pressure area passes, the winds usually increase in strength. Perhaps the two effects cancel. At any rate in looking over the summer bathythermograms, one does not gain the impression that gradual variations in the thickness of the wind-stirred layer are produced by passing wind systems.

A much more obvious effect of the winds is to transform horizontal temperature gradients into vertical gradients. Because the temperature of the wind-stirred surface layer increases gradually from north to south in the Northern Hemisphere, a southerly wind will often cause warmer water to overlie colder water. The opposite is not so often true, unless the horizontal gradient is very sharp, for a north wind is usually a relatively cold wind and therefore effective in maintaining a deep mixed layer. In any case, unless there is also a horizontal salinity gradient, a north wind would tend to produce an unstable situation.

Of much greater practical importance is the effect of local winds on waves and vertical mixing. Areas where winds are variable are also variable from the standpoint of echo ranging. During occasional violent storms, echo ranges are reduced by heavy seas. There is also more calm weather, particularly in summer, so that "afternoon effect" and shallow mixed layers are common. Thus on the average, sound conditions are poorer in the mid-latitudes than in regions such as the trades where there are steady, moderate winds. On the other hand they are generally better than in the subpolar regions where winds of gale force interfere with echo ranging most of the time.

In its total aspect the state of the sea depends on many factors: on the velocity of the wind, the length of time it has been blowing, and the fetch (the distance upwind that the speed and direction remain roughly the same); on whether the wind is rising or falling; on the temperature of the air and the difference in temperature between the air and the water. However, of all these, the velocity of the wind is by far the most important. The average seasonal and geographic variations of the wind force are well known, and climatic atlases summarize the information in a more or less convenient form. Figures 1 and 2 show the frequency of winds stronger than force 6 (Beaufort) in winter and in summer. The incidence of strong winds, as well as the temperature gradient near the surface, is considered in preparing the Periscope-Depth Range Sonar Charts.

8.2 EDDIES

Currents throw off eddies which vary in size from a few miles to perhaps 75 miles in diameter, large ones being common on either side of the Gulf Stream between Cape Hatteras and the Grand Banks. North of the current the eddies contain relatively warm water near the surface and are easily detected. Those to the south of the Gulf Stream contain water which is only slightly warmer than that already in the invaded area, but the larger of these eddies can be made out from the trend of the deeper isotherms. From the acoustical standpoint the edges of eddies are much the same as the edge of the current itself. A shallow layer of one temperature will be found overlying a layer of some other temperature.

How long such eddies persist and retain their thermal characteristics near the surface is not well known. Large eddies near the Gulf Stream are known to have persisted for more than a month, but the sur-

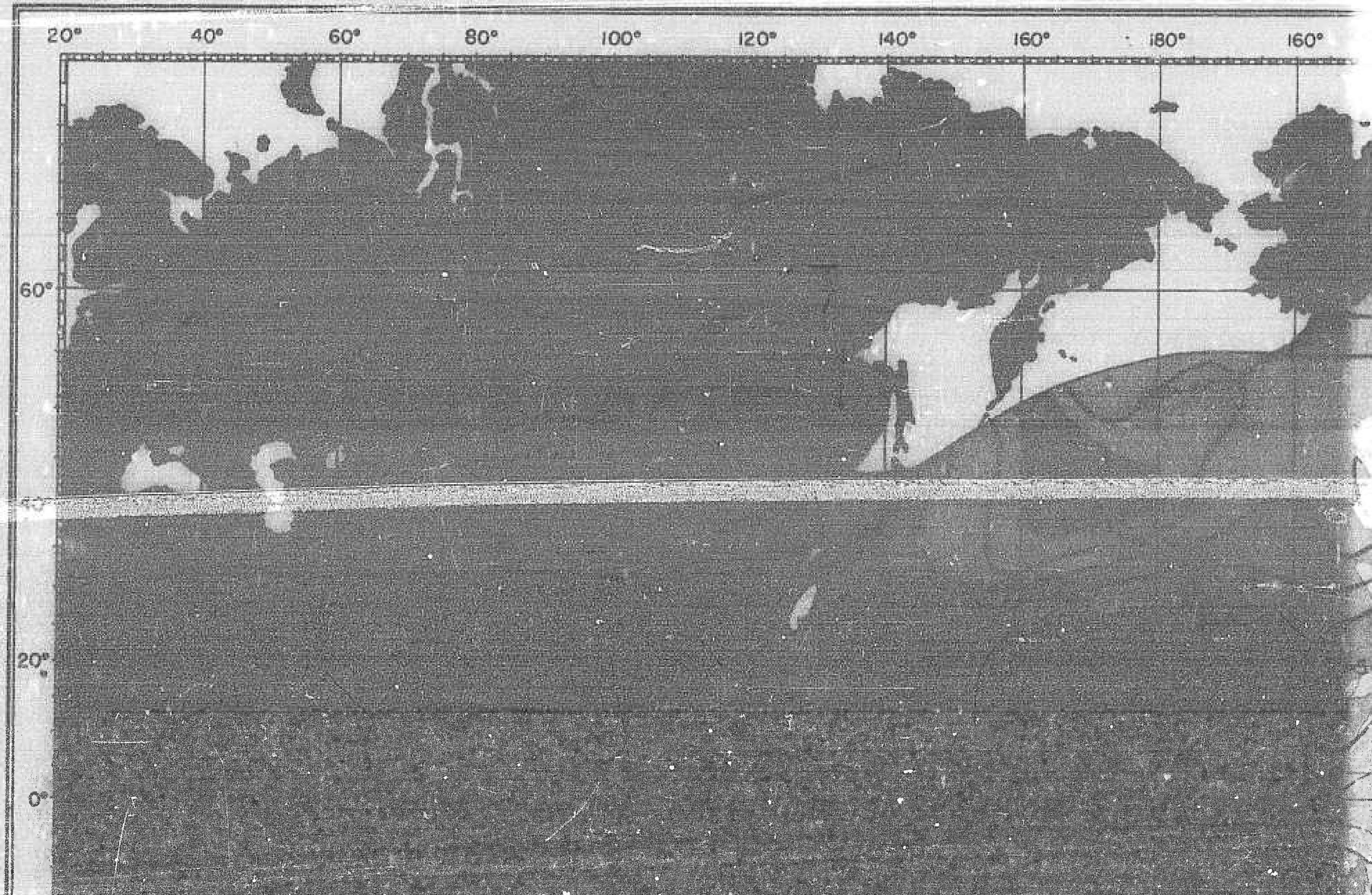

FIGURE 1. World chart showi[illegible] [illegible]equency

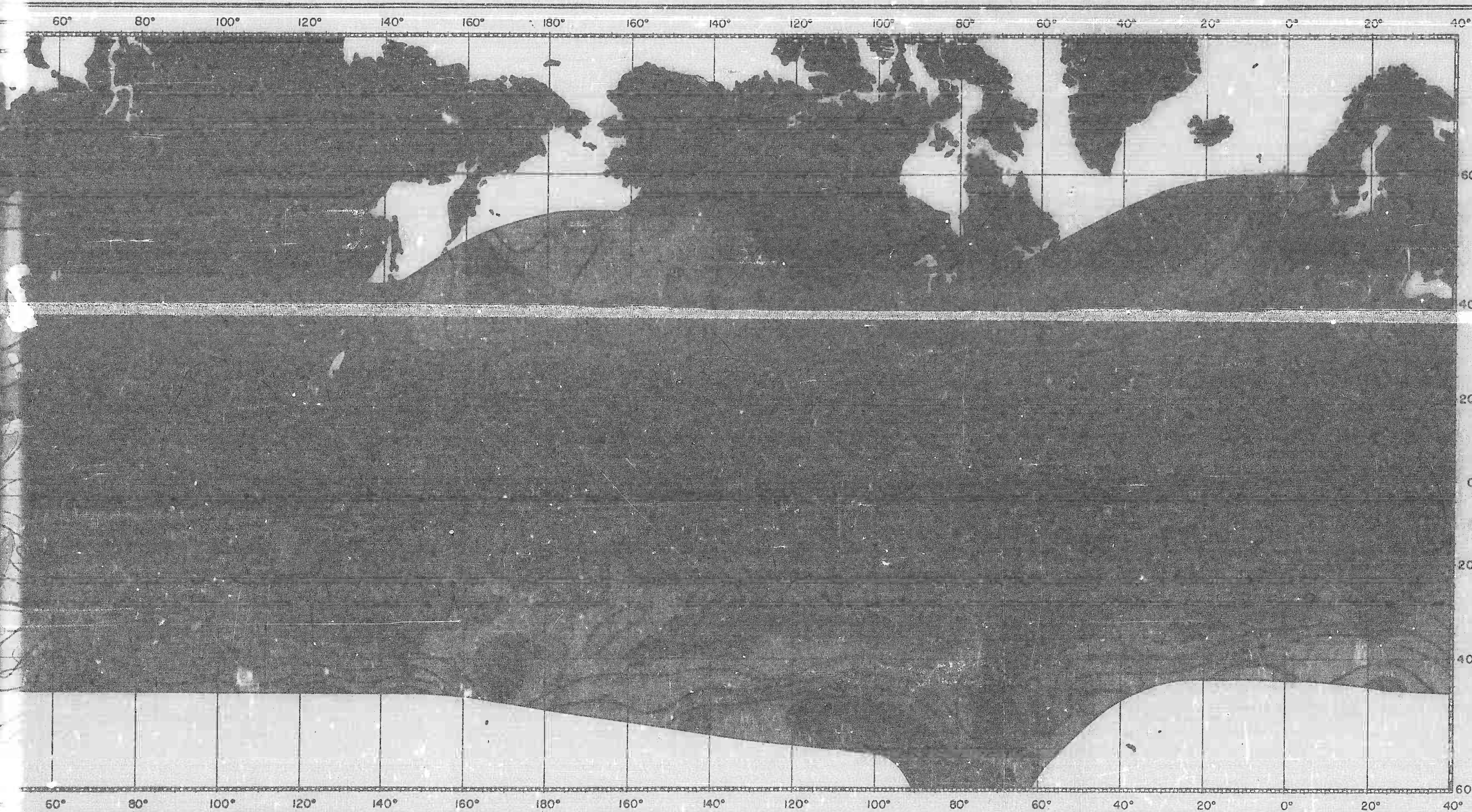

FIGURE 1. World chart showing percentage frequency of winds greater than force 6 (Beaufort) in February.

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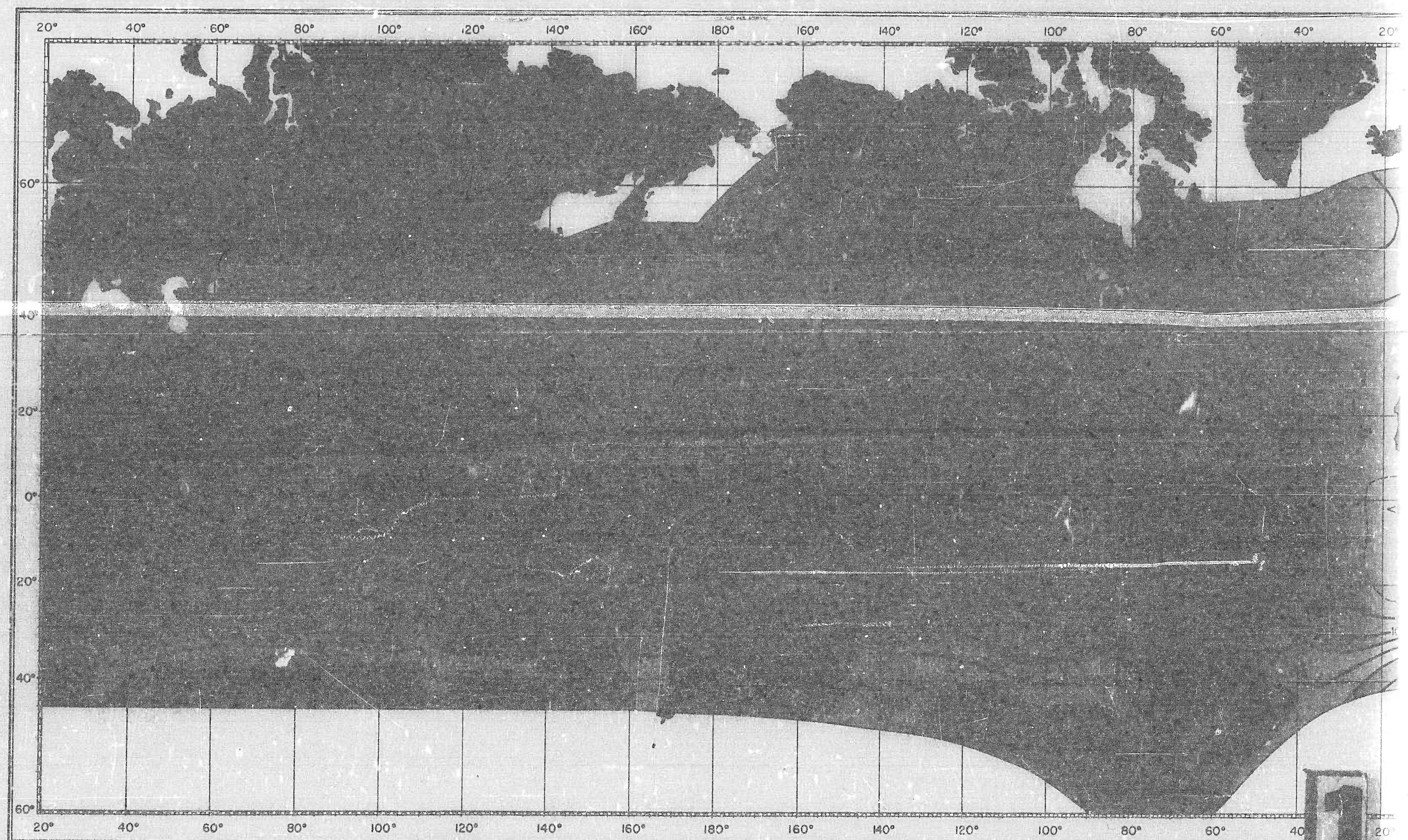

FIGURE 2. World chart showing percentage frequency of winds greater than force 6 (Beaufort) in August.

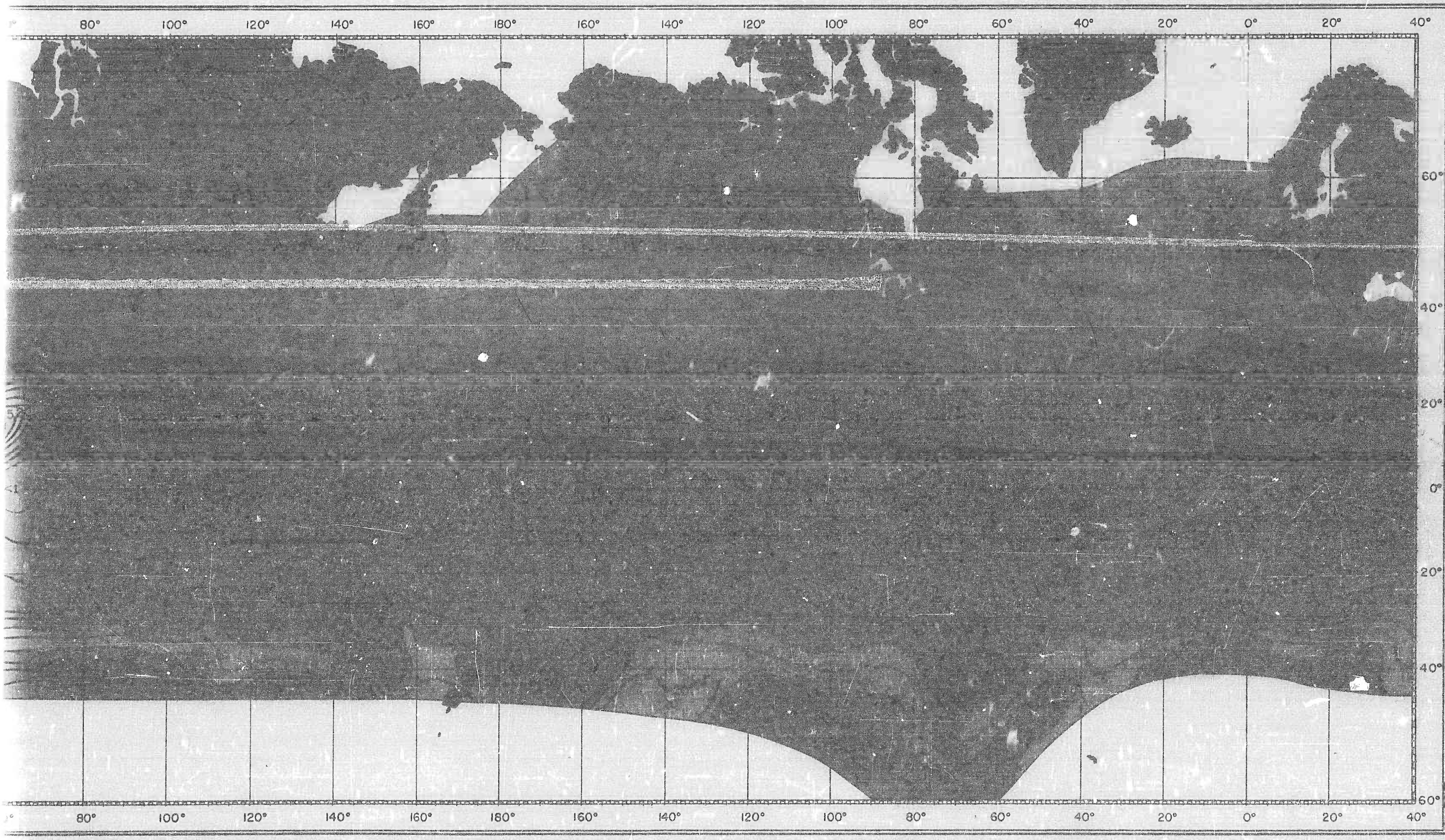

FIGURE 2. World chart showing percentage frequency of winds greater than force 6 (Beaufort) in August.

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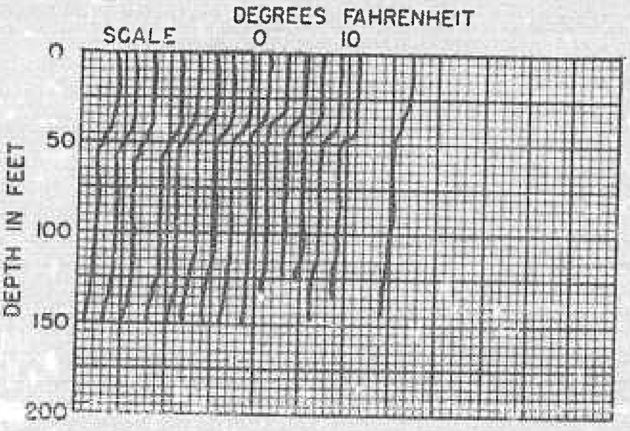

FIGURE 3. Bathythermograms illustrating internal waves.

face velocities when they first form may be as much as 2 knots. Presumably smaller eddies have much less momentum and soon die down, or at any rate their surface characteristics are soon destroyed by wind stirring. However this may be, eddies are a potential source of poor and variable sound conditions.

Eddies have seldom been fully delineated. Usually a single line of temperature observations crosses what might be a roughly circular core of warmer water or a tongue of warmer water extending back to the source.

8.3 INTERNAL WAVES[a]

The waves hitherto considered have been displacements of the surface of the sea. However, waves can occur not only in the air-water boundary but also in the interface between strata of water of different density. These internal waves, as they are called, have been observed both in the main thermocline and in the seasonal thermocline. Their effect on subsurface warfare has not yet been fully investigated, but there is no doubt that they are responsible for some of the observed variations in sonar performance.

The difference in density above and below a thermocline is of course much less than that between the air and water at the surface of the ocean. Thus a boundary within the ocean itself can be much more easily displaced than the surface of the sea, and the waves in the boundary set up with correspondingly less energy. Theoretical considerations not only indicate that such waves do exist but also predict their properties. The waves have their greatest height at the interface between the two layers and their amplitude diminishes rapidly above and below it, approaching zero at the surface and bottom of the ocean. The theory shows further that internal waves can be formed not only at a boundary where the density changes abruptly but also in water in which the change is more gradual. On the other hand, there are no internal waves in homogeneous water in which the density does not change with depth.

That internal waves are present in the ocean in fact as well as in theory has been proved by measuring the variation with time of the temperature, salinity and oxygen content at various depths. Before the war, measurements were made in a series with sample bottles and reversing thermometers from an anchored or slowly drifting ship. As each lowering required an appreciable time, there was a time interval of more than 1 hour and sometimes as much as 2 hours between successive lowerings. This meant that only long period waves could be found by these methods.

In this way internal waves were found with periods of 24 and 12 hours, corresponding to the periods of the tides, and with heights as great as 300 feet. There was some evidence of waves with shorter periods, but the periods found by this method had to be at least as large as the interval of 1 to 2 hours between successive lowerings.

In order to find out whether there were any waves of shorter period it was necessary to make lowerings in much more rapid succession. For this purpose the *bathythermograph* [BT] has provided a greatly superior instrument. Series of lowerings every two minutes for as long as 24 hours have been made. A few bathythermograms from such a series are reproduced in Figure 3 to show the kind of variations that are obtained.

It is convenient to represent these waves graphically as a depth curve along which the temperature is constant, plotted against time. In an ocean with no internal waves, these lines would be straight and horizontal; but owing to the irregular raising and lowering of the layers by the internal waves, the lines are moved up or down until they represent the form of the waves. One of these 24-hour series, shown in Figure 4A without the small-scale features, is characteristic of all the records that have been obtained off San Diego. The tidal period is evident in the long

[a] A memorandum by C. W. Ufford of UCDWR, dated May 15, 1945, summarized work on internal waves and provided most of the information in this section.

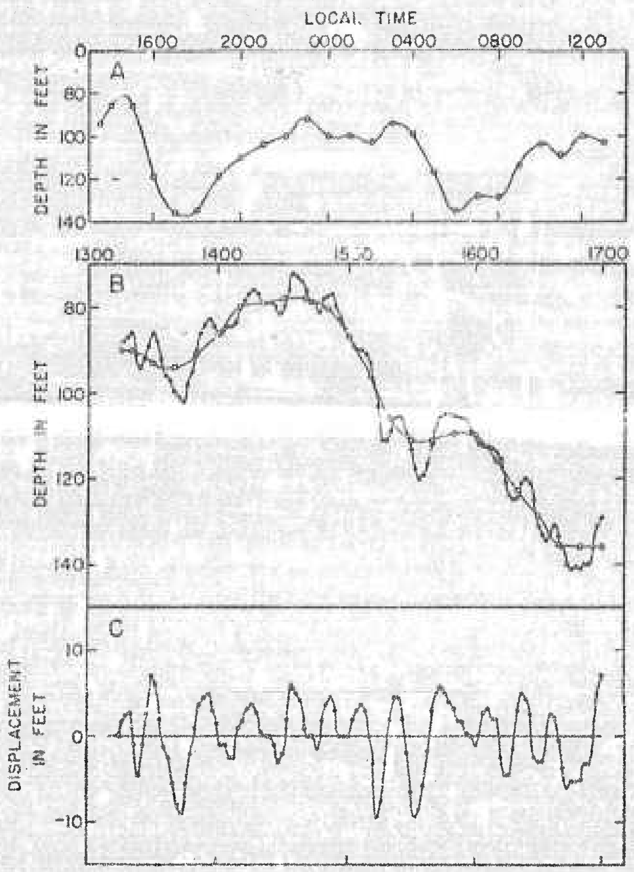

FIGURE 4. Internal waves illustrated by plotting the depth of an isotherm against time.

sweep of the curve. Waves of shorter period are superimposed upon the waves of long tidal period. The first section of the curve of Figure 4A is reproduced on a larger scale in Figure 4B, which shows the shorter period waves oscillating around the average curve representing the tidal period. If, in Figure 4B, the curve of tidal period is subtracted from the short period curve, the resulting waves are as shown in Figure 4C.

In addition to the lowering of bathythermographs from surface ships, a series of observations made aboard a submarine showed that while balanced on a seasonal thermocline its depth varied periodically, revealing the existence of internal waves with periods of 8 to 10 minutes and heights of about 20 feet. These observations are described in more detail in the summary volume on diving control. On another occasion, in experiments off San Diego, a submerged submarine ran through internal waves, maintaining a constant depth with its planes, and recorded periodic variations in the temperature at that depth. Calculations based on these observations indicated that the period of the waves was about 5 minutes and the largest height 28 feet.

Experiments have also been made to find the velocity and length of internal waves. In order to do this it is necessary to make BT lowerings simultaneously from at least three positions on the same ship or from three ships anchored in a triangle. The results of measurements made thus far suggest that the waves travel with a speed of about half a knot and have wave lengths of about 250 yards. Figure 5 shows a set of observations made aboard a single ship with BT installations at the bow, amidships, and at the stern. The order in which the curves on the figure progress indicates that the waves came from the direction in which the ship was heading and successively passed under the three installations.

The practical consequences of internal waves in

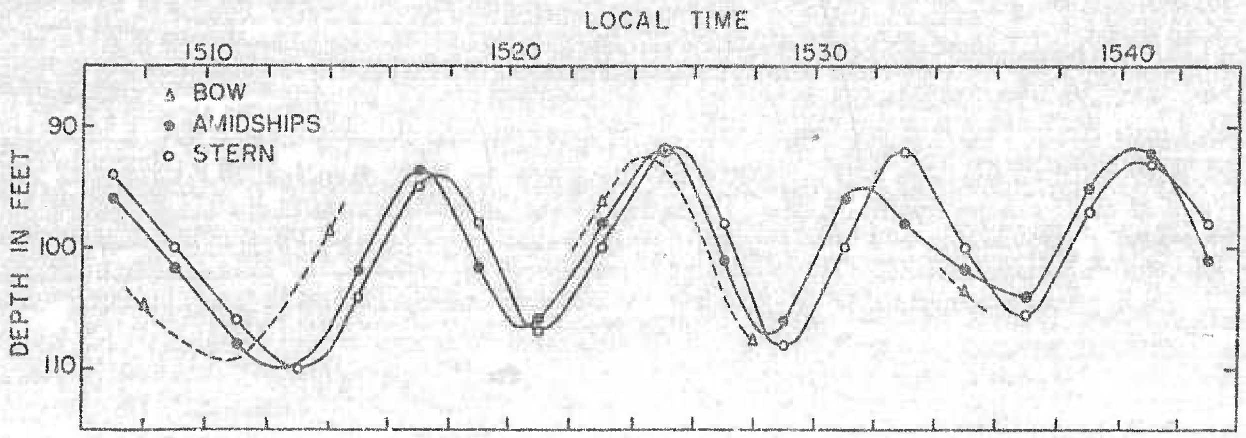

FIGURE 5. Progression of internal waves demonstrated by simultaneous bathythermograph lowerings at three positions on a ship.

submarine operations are discussed in the summary volume on diving. The very important acoustical consequences have only graduall, and quite recently become apparent.

With the passage of each internal wave the depth of the nearly isothermal surface layer varies. Because of the changes both in layer depth and in the strength of the underlying negative gradient, the assured range can be expected to vary. Thus internal waves are one cause of variability in maximum ranges, although not a particularly serious one. It would not be surprising, for example, to find that the range on a submarine below layer depth varied 200 or 300 yards from one attack to the next because of the effect of an internal wave, but variations much greater than this would be fairly uncommon. Thus, over a period of several hours, the variations in maximum range caused by oscillations of layer depth would be no greater than those produced by other variables such as submarine aspect. Occasionally as the crests or troughs of the longer period (12 hours or so) waves passed, the sound conditions might change significantly, but under operating conditions horizontal temperature gradients could have as great an effect in any such period of time.

It seems probable, however, that internal waves affect sound transmission in still another way.

Every sound operator and antisubmarine warfare officer is well aware of the fact that there is a great variability in the quality of submarine contacts which cannot readily be explained by the routine BT classification. One attack may be spoiled by lack of information due to the intermittent and mushy quality of the echoes, and the next attack, under apparently identical conditions, may be a good one. Theory suggests that internal waves may be at least partly responsible for such variability. The simple refraction theory is based on the assumption that the temperature strata are essentially horizontal out to the limit of sound beam penetration. This assumption is obviously not correct when internal waves are present.

As the sound beam travels nearly horizontally at or near layer depth, there will be regions behind each wave in the surface of the thermocline where little or no sound strikes the thermocline, since it has been bent down by striking the slope of the wave facing the projector. This means that sound is removed from parts of the sound field where it would appear if the thermocline were entirely level. On the other hand, internal waves could in some cases account for the penetration of sound into areas where the simple refraction theory would predict a shadow zone. As the internal waves progress all these effects will contribute to the variability that is one of the most striking characteristics of the sound field.

8.4 MICROSTRUCTURE

Attempts to measure very small-scale thermal structure in the open ocean are beset with very great difficulties. The rolling and pitching of the ship, and the swinging of the thermometer on its supporting cable are only a few of the obstacles which have to be overcome in order to distinguish between vertical and horizontal gradients. Nevertheless, there is a good deal of more or less indirect evidence that small but sharp temperature gradients exist in the water which may serve to scatter sound.

In the first place, even the BT, crude as it is for studying small-scale thermal structure, occasionally shows up surprising detail, which is reproduced in both the up and the down traces, and is therefore vertical structure. Figure 6 is a magnified reproduction of BT traces taken in Guantanamo Bay, Cuba, which show pronounced development of successive strata of water, each with a relatively uniform temperature and separated from the next by a sharp discontinuity. The lowerings were made slowly on a hand-line paid out from a dinghy in order to record the temperature with the greatest possible accuracy and freedom from vibration. In each figure the down trace is on the right and the up trace on the left. Failure of the traces to coincide is due to lag in the thermal response of the instrument used and to the fact that it was hauled in more quickly than it was paid out, which tended to smooth the temperature traces. Nevertheless, there is sufficient agreement in each pair of traces to leave little doubt that valid measurements of vertical structure were obtained.

Measurements of vertical sound velocity gradients[2] reveal small-scale variations which are presumably largely due to temperature changes and therefore are indicative of thermal microstructure. The observational method used did not preclude the possibility that part of the recorded variations were caused by vertical oscillations of the instrument through the water or by horizontal gradients, but comparison of down and up traces shows that some vertical microstructure existed. However, the interest in this work

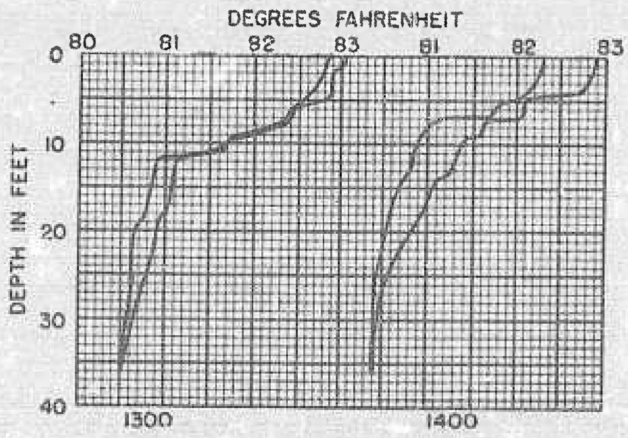

FIGURE 6. Bathythermograms illustrating microstructure.

does not lie in its accuracy as a means of studying microstructure but rather in the fact that it is a concrete demonstration of the existence of small scale variations in velocity within the sound field which can be in part responsible for variability in sound transmission.

Attempts to measure small-scale horizontal structure have not been very successful, although it is fairly clear that near the surface convection cells, when they are well developed, must cause just such thermal structure. The temperature increase has been measured[3] between depths of 3 and 20 millimeters and has been found to be as much as 1.8 F, averaging about 0.8 F. This gives some idea of the maximum degree of thermal instability that can arise through surface cooling and of the maximum amount of horizontal variation that might be expected when the surface water drains into the convergences of convection cells. Thus far no accurate measurements have been made of the temperature differences within these convergences, although in horizontal temperature measurements at various depths some evidence has been reported[4] of small-scale cyclical variations of about 0.02 degree occurring about every ten yards in waters that were investigated off San Diego, as well as occasional larger discontinuities of the order of 0.5 degree.

The acoustic effect of microstructure has not yet been measured accurately, but qualitatively it is fairly obvious how it affects sound transmission. A steplike thermocline of the kind pictured in Figure 6 is in reality a series of little thermoclines of varying degrees of steepness. Moreover, they are not horizontally continuous throughout the entire sound field because every BT lowering shows a slightly different pattern. The combined effect is that the individual refraction paths of sound rays are highly variable, leading to irregular variations in intensity within the sound field. Probably microstructure is one of the more important causes of varying intensity from one echo to the next, as contrasted with the internal waves previously discussed, which would be more likely to produce larger scale fluctuations of a more regular nature over a period of several pings.

Chapter 9

COASTAL WATERS

NEAR most continental coast lines the vertical structure of the water column is so different from that prevailing in the open ocean as to warrant separate discussion. This is especially true of coasts having a broad continental shelf, where large or many rivers drain into the sea, or where offshore winds prevail. In general, the situation in coastal waters tends to be specialized through one or more of these causes. Vertical gradients of temperature and salinity are often much more pronounced than offshore, and the seasonal changes are usually greater also. The 100-fathom contour roughly marks the boundary between coastal and offshore water, although in special circumstances water which is clearly of coastal origin can be encountered 100 miles or more beyond the limits of the continental shelf. The currents in coastal waters, which are caused by density gradients and by local winds and tides, are complex and interesting oceanographically and highly important from a practical standpoint both in navigation and in echo ranging. The type of bottom also is influential in determining whether sound ranges will be improved by multiple reflections or will be shortened by masking reverberation.

9.1 COASTAL CIRCULATION

9.1.1 Density Currents

Because of land drainage the density of coastal water is usually less than at corresponding depths offshore. Along any coast where there is a significant amount of freshening due to land drainage, there is a general tendency for the fresh water to move offshore on the surface and the denser (more saline) water to move in underneath. Thus the salinity of the surface water increases from the shore outwards, and furthermore there is an increase in salinity from the surface downward. This is an unstable condition in that the density surfaces slope downward in an inshore direction, and the unequal pressure gives rise to currents which in general behave according to the principles of the circulation theory.

Since the density surfaces slope downward toward the shore line, the direction of the currents is roughly parallel to the coast, with the coast on the right-hand side of the direction of flow in the Northern Hemisphere and on the left-hand side in the Southern Hemisphere.

As a result of this prevailing situation, in the Northern Hemisphere the coastal currents on the west side of the oceans are usually south-flowing and therefore relatively cold as shown in Figure 1, which is a temperature section across the Labrador Current. The observations were made in spring, and seasonal warming had affected the surface water. However, this did not obscure the fact that the inshore water

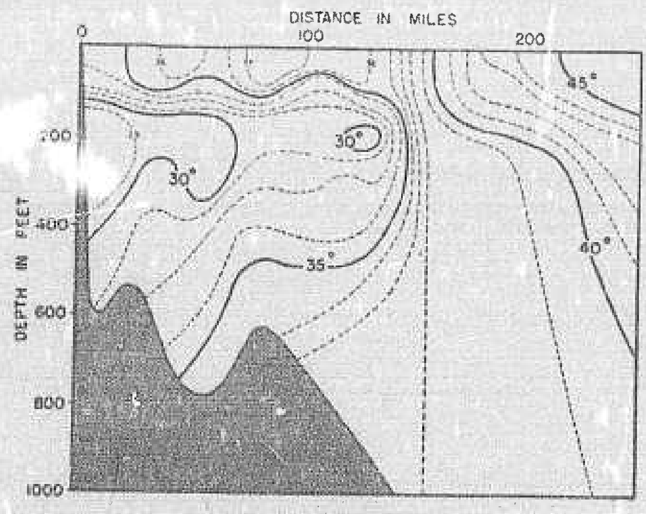

FIGURE 1. Temperature profile across the Labrador Current.

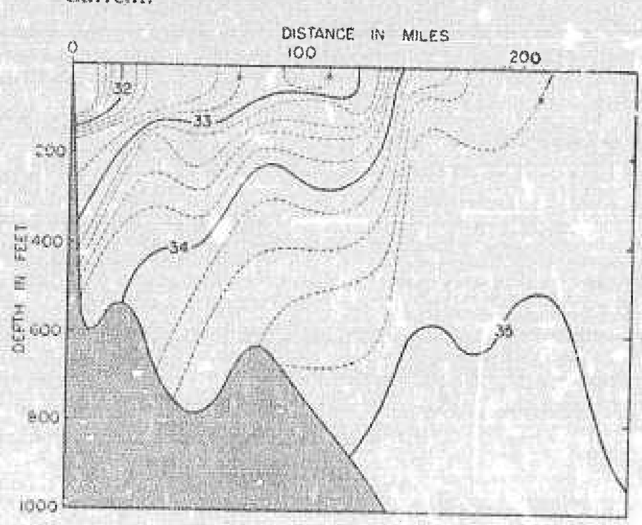

FIGURE 2. Salinity profile across the Labrador Current.

that had come down from the north was much colder than the water further offshore. Figure 2 is a salinity section of the same water. The salinity is least near shore and at the surface. Salinity is responsible for the density gradient that sets up the current. since from the standpoint of temperature alone, the inshore water obviously would be heavier rather than lighter.

Along the east side of the oceans, coastal density currents generally flow northward and therefore are warmer than the offshore water. Thus both temperature and salinity contribute to the density gradient between inshore and offshore water.

Exceptions to these general statements occur where the continental shelf is narrow and where little river water is brought down to the sea. In such cases local winds and seasonal variations in rainfall are important in determining whether or not a typical coastal current will develop. For example, on the east coast of the United States there is a well-developed coastal current as far south as Fort Pierce, Florida. Beyond that point the shelf narrows rapidly and the coastal current, known as the Florida Countercurrent, becomes weak and sometimes very nearly nonexistent. The coastal water off Miami is slightly cooler than the northward flowing Florida Current offshore (see Figure 19, Chapter 7). It is also slightly fresher, enough so that the countercurrent generally flows during the wetter months of the year. During the spring and summer months, however, steady southeasterly breezes carry the Florida Current close inshore, and the coastal current is either obliterated entirely or is driven below the surface where it can be detected only by the BT or by other subsurface sampling methods.

A somewhat similar situation occurs off the California coast. Figure 3 shows the oceanic California Current flowing well offshore and the coastal current known as the California Countercurrent which flows northward closer inshore. The latter is typical in so far as it is a warm, north-flowing current, but the temperature difference is slight, and there is not enough coastal drainage to produce a significant salinity gradient. Hence it is weak and diffuse, frequently permitting the development of still another countercurrent close inshore, as shown in the figure. During the summer, when the prevailing winds are offshore, the coastal current occurs only in the subsurface waters and is replaced at the surface by a complex circulation resulting from upwelling.

The extent to which a current parallels a coast depends to a considerable extent on the difference in density between inshore and offshore water. When the density difference is slight, the current may frequently be set onshore or offshore. The directions that it takes will be dependent to a large degree on bottom topography. Frictional retardation by bottom particles in contact with a current not only affect its velocity but also its direction. The tendency is for the normal twisting to the right (in the Northern Hemisphere) to be accentuated as the current moves over a shoaling bottom and to be lessened over a deepening bottom. Thus when the water is relatively homogeneous it is common to find an inshore set towards reefs and inlets (Figure 4).

9.1.2 Local Wind and Tidal Currents

With an onshore wind, surface water is transported toward the land, with the result that the surface layer thickens near the beach. With an offshore wind the warm surface layer is removed and the underlying thermocline approaches the surface. This process is called upwelling, although the term is somewhat misleading, as little vertical motion is involved.

Where steady offshore winds prevail, as in the trade wind belt, upwelling may be a more or less continuous phenomenon. The mixed surface layer is carried offshore by the wind as fast as it is formed. Examples are the west coast of Africa in the region of Dakar and the Gulf of Panama. To a lesser extent similar conditions occur on the lee side of islands in the trade wind belt.

Along the east coast in higher latitudes, upwelling may occur as a result of strong offshore gales in winter. Several oceanographic stations made in February on a line across the Nova Scotian continental shelf show a mixed surface layer only about 100 feet deep overlying much warmer and more saline water. The strong positive gradients thus produced would give a deep submarine almost complete protection against sonar detection.

While no other winter temperature observations are available from this area, it is believed that normally a much deeper isothermal surface layer would be found with positive gradients confined to the outer third of the continental shelf. At any rate that is the prevailing situation further south. A possible explanation of these relatively shallow and sharp positive gradients off Halifax is that strong offshore

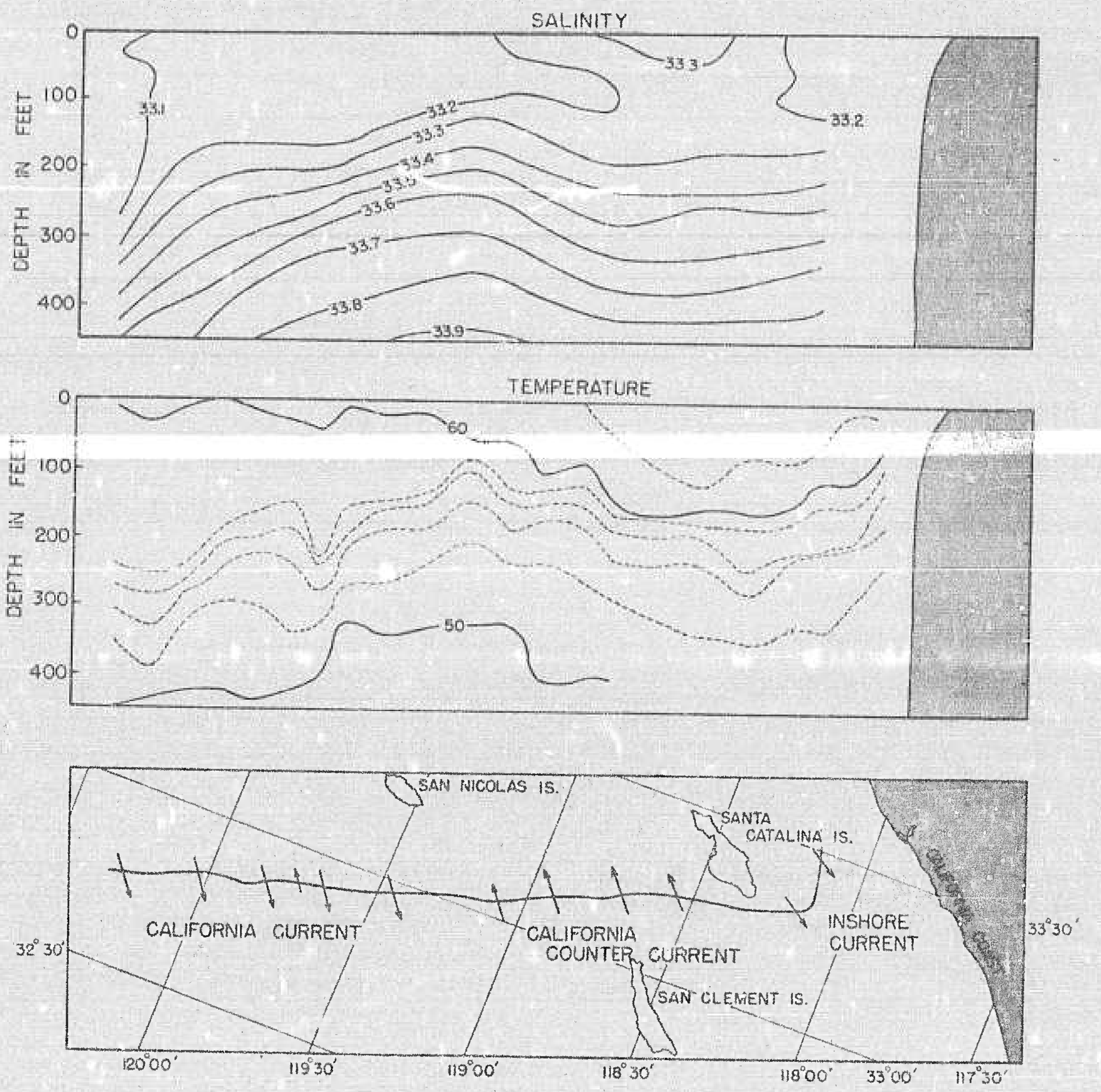

FIGURE 3. Temperature and salinity profiles across the California Currents.

winds had recently removed much of the superficial layer from the continental shelf and that this water had been replaced by a deep indraft of much warmer and more saline oceanic water.

Apparently on a broad continental shelf, as off Halifax, bottom friction and the strong southward flowing coastal current are usually able to combine in preventing all of the coastal water from being blown out to sea by the prevailing offshore winds. Nevertheless, a certain amount of upwelling must obviously occur. Where the continental shelf is narrow and the coastal current is weak because of lack of land drainage, offshore winds will be much more effective in decreasing the depth of the mixed surface layer close to the coast and thus reducing the effective echo range.

The converse to upwelling, the accumulation of warm surface water near a coast by an onshore wind, improves sound conditions and is equally common. It is a special case of convergence, just as upwelling is a special case of divergence.

Tides are a form of wave motion, and as such their behavior is in many respects similar to that of wind-driven waves. In the open ocean where the height of

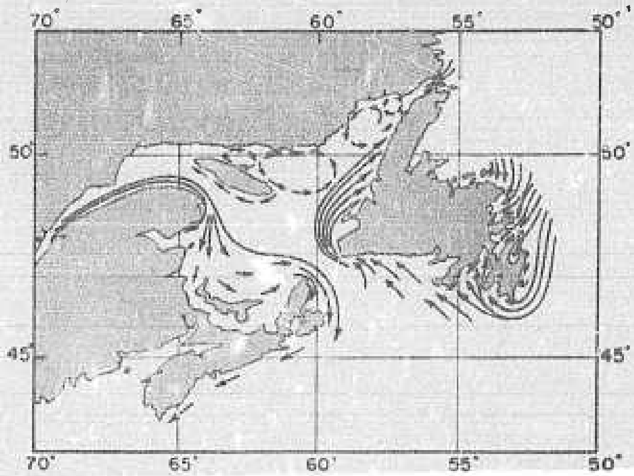

FIGURE 4. Configuration of surface currents, Newfoundland area.

the wave is less than 3 feet and its length several hundred miles the orbital movement of water particles in the wave extends to the bottom. The mass transfer of water involved in this movement is large, but the horizontal displacement of individual particles is small. However, as the wave approaches shoaling water the horizontal components of flow are greatly increased because of the decreasing cross sectional area. The resulting tidal current is accompanied by a shortening of the wave length and an increase in the height of the tide.

In a restricted area such as a channel, tidal currents generally flow back and forth, reversing direction with each tidal period. In more open shallow waters tidal currents have a rotary motion which is apparently an effect of the earth's rotation. The direction shifts around the compass during each tidal period (generally every 12 hours), and any given water particle in the tidal stream describes a roughly elliptical course.

Georges Bank off the Gulf of Maine provides a notable example of the effects of strong tidal currents. Immediately north of this bank in the deeper waters of the Gulf of Maine there is a pronounced seasonal cycle with well-established vertical stability (Figure 17). To the south of it is a typical slope water area (Figure 40, Chapter 5). But inside the 50-fathom contour on the bank itself stability develops only briefly and intermittently during a short summer season whenever the winds happen to be light for several days at a time. At all other times tidal stirring and winds keep the water column mixed from surface to bottom. As a consequence relatively low surface temperatures are encountered over the bank in summer. This of course explains the widespread reputation of Georges Bank for fog. Another result of the strong tidal stirring is that near the edges of the bank rather special hydrological conditions are found where the mixed waters of the bank are in contact with the stable waters surrounding it. This is illustrated in Figure 5 which shows the temperature across Georges Bank in northwest-southeast profile in June 1939. Not only are the sound conditions, provided reverberation is not limiting, markedly better over the bank than on either side, but also a submarine crossing such an area would find that trim for resubmergence would alter significantly.

Tides and variable winds also affect the speed and direction of coastal currents. As their velocity varies,

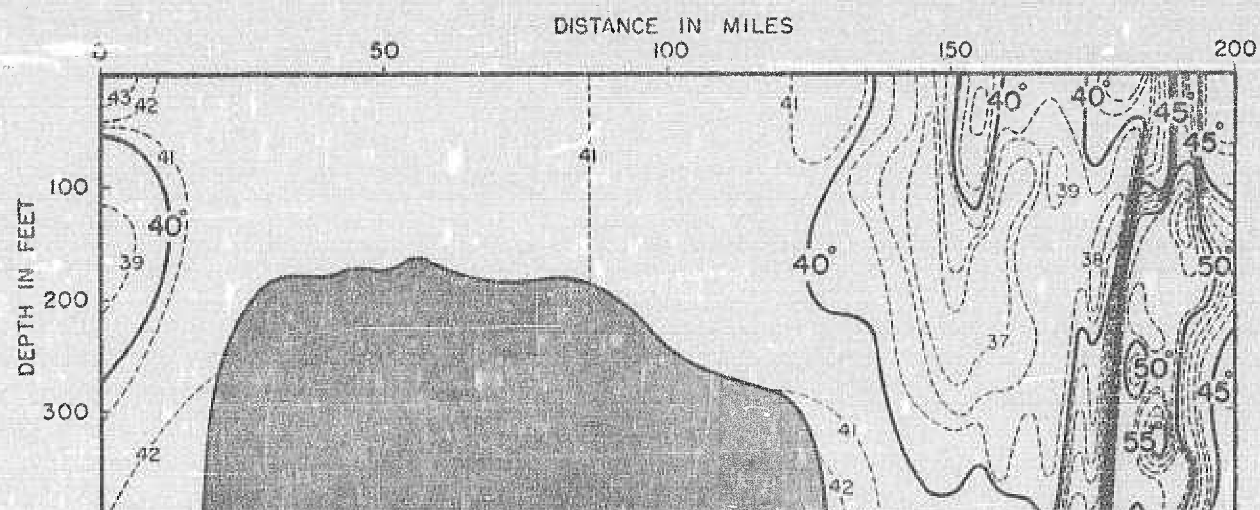

FIGURE 5. Temperature profile across Georges Bank.

more or less crosscurrent transfer takes place. This is usually offshore at the surface and inshore along the bottom. It is the inshore component near the bottom which is especially significant, for it is this which is chiefly responsible for the large vertical salinity gradients typical of coastal waters. Especially where deep gullies cross a continental shelf, highly saline water will be able to move in close to the land, while above it much fresher surface water will be moving along shore, occasionally with a slight offshore component. It is important to remember that if coastal waters are not to become fresher and fresher, there must be an inward movement of saline water along the bottom, which through vertical turbulence carries salt up to the surface. The stronger tidal currents near the coast are favorable for such vertical mixing, but the high thermal stability typical of the summer season has the opposite influence.

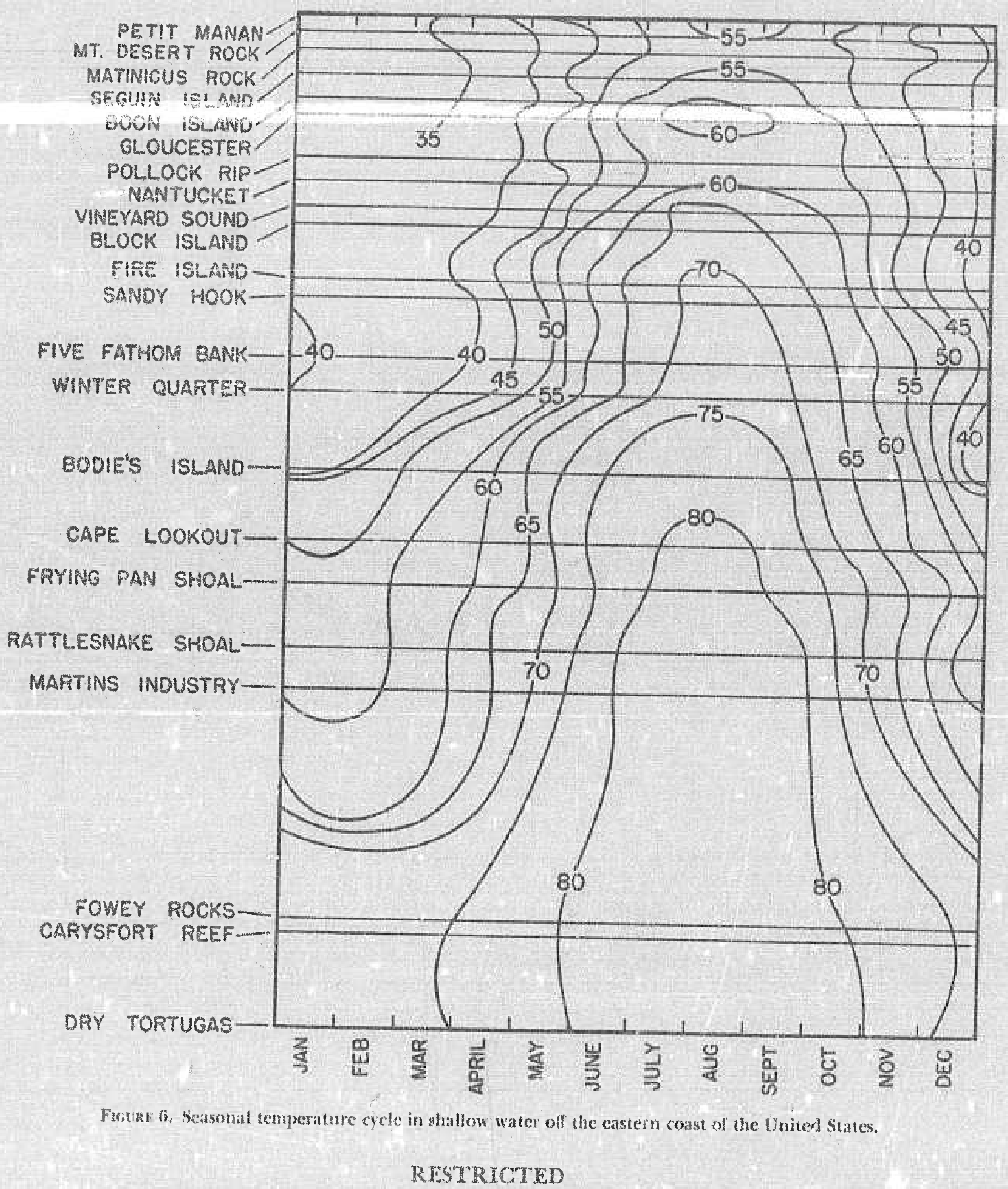

FIGURE 6. Seasonal temperature cycle in shallow water off the eastern coast of the United States.

From the foregoing discussion, therefore, it is apparent that tidal currents have a direct effect on all phases of coastal submarine warfare in the following ways: first, they tend to destroy vertical temperature and salinity gradients, and second, in many localized areas they produce mixed water where otherwise it would not exist. This naturally improves echo ranging conditions. It also simplifies diving operations of submarines but at the same time makes evasion more difficult.

9.2 VERTICAL DISTRIBUTION OF TEMPERATURE AND SALINITY

Except in a few specialized areas in low latitudes, the vertical temperature gradients in coastal waters are dominated by the seasonal cycle. In general, coastal waters are sufficiently shallow so that in winter the whole water column becomes isothermal. Thus there is no counterpart to the main thermocline of the open ocean.

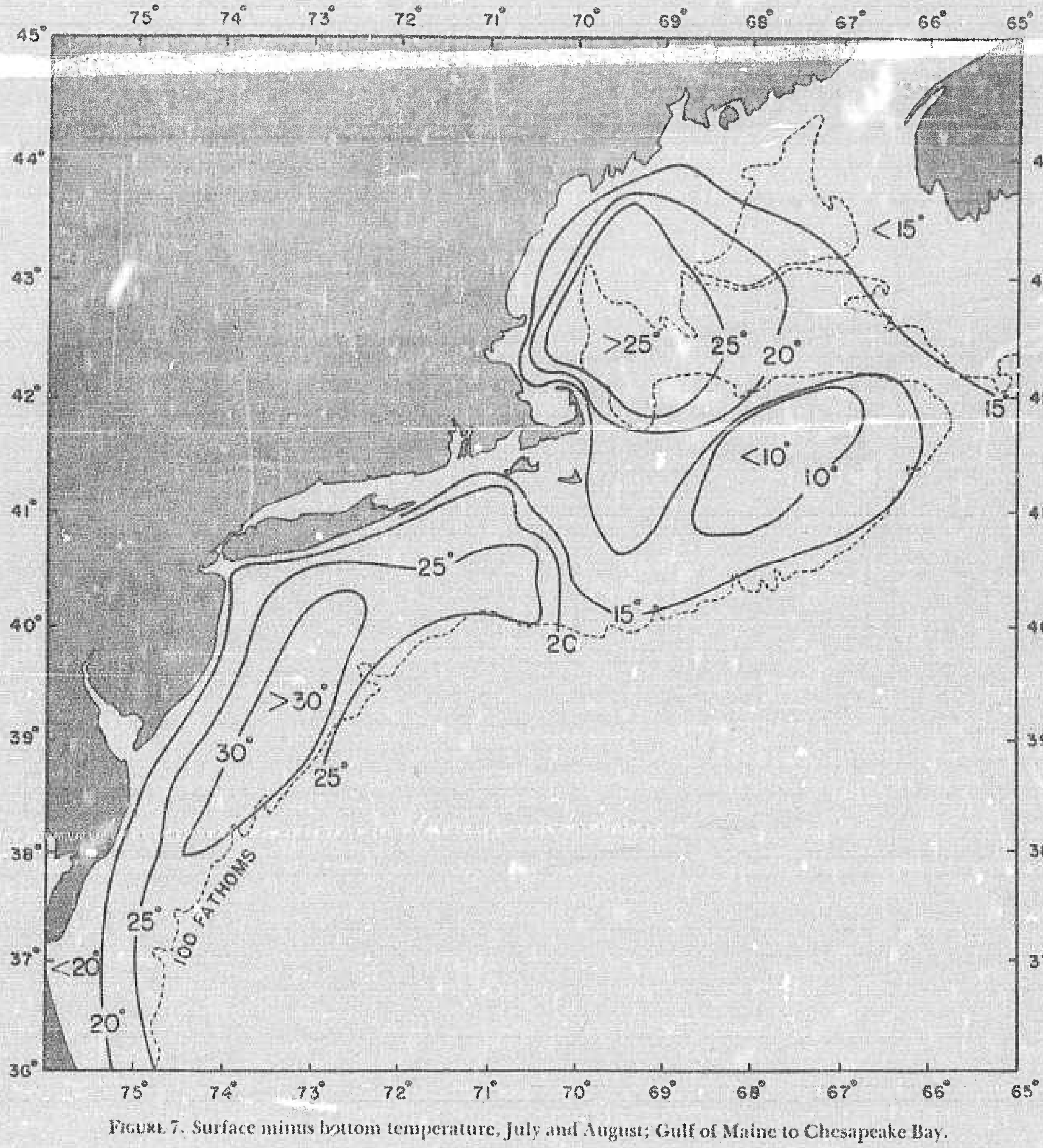

FIGURE 7. Surface minus bottom temperature, July and August; Gulf of Maine to Chesapeake Bay.

The available BT observations permit illustrating the seasonal temperature cycle in most detail for a large area along the eastern coast of the North Atlantic. The many oceanographic stations which are available from the western North Pacific indicate that the coastal conditions there are entirely comparable.

Close to the beach the relatively strong tidal currents and the shallowness of the water usually prevent marked thermal stability from developing out to roughly the 10-fathom contour. With this in mind, a useful sort of diagram has been developed from the routine surface temperatures collected from lightships along the Atlantic Coast (Figure 6). It gives a fairly representative picture of the seasonal temperature changes at the surface as a function of latitude and although these are inshore surface temperatures, they are on the average only slightly lower at any given latitude than the surface temperatures across the whole continental shelf.

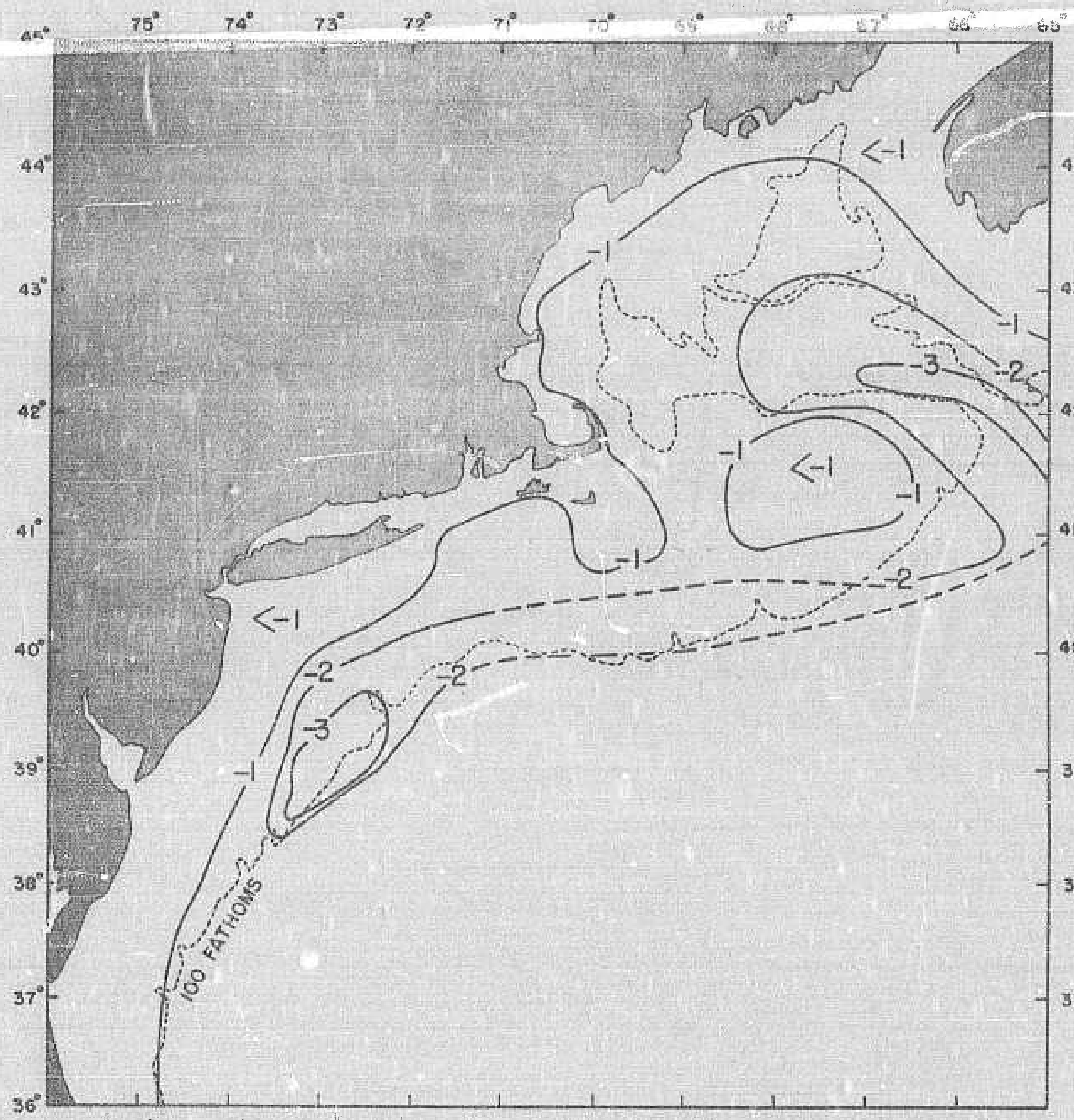

FIGURE 8. Surface minus bottom salinity, July and August; Gulf of Maine to Chesapeake Bay.

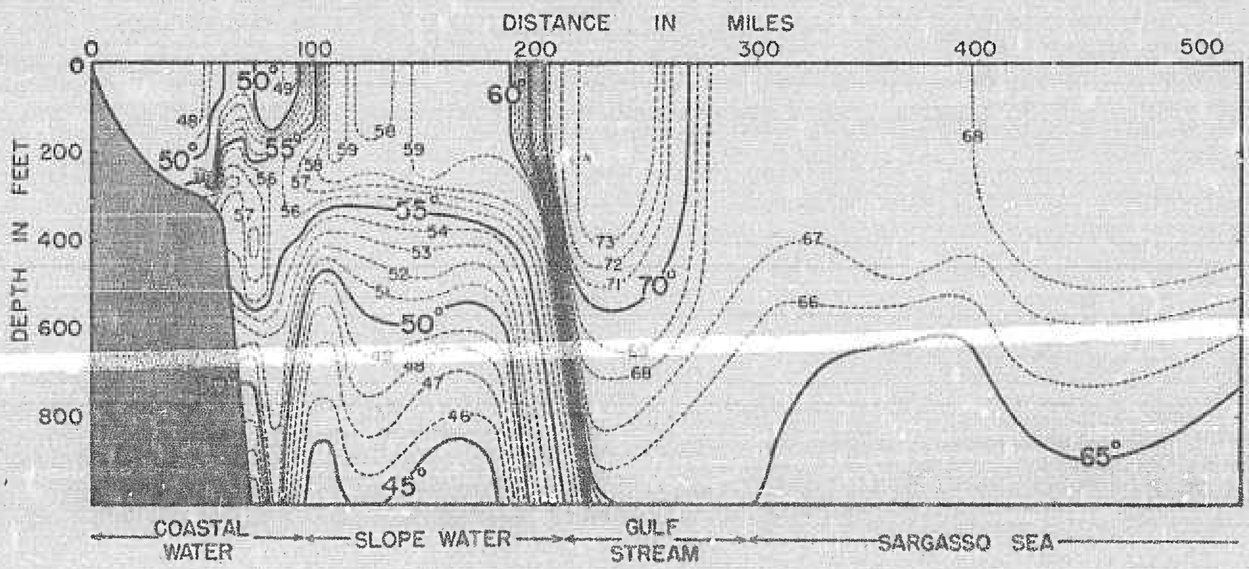

FIGURE 9. Temperature profile SE from Montauk Point in midwinter.

Detailed studies have been made of the distribution of temperature and salinity in the Gulf of Maine and southward over the continental shelf to Cape Hatteras. For the present purposes, the significant conditions over this area can be summarized in two diagrams: the first (Figure 7) shows the average difference in temperature between the surface and the bottom in July and August, while the second (Figure 8) shows the magnitude of the vertical salinity gradient at the same season. Thus it will be seen that in summer over much of this area surface temperatures are from 20 to 30 degrees higher than at the bottom, while the surface waters are from 1 ‰ to 3.5 ‰ fresher than at the bottom. The resulting vertical change in the speed of sound is therefore generally greater than 150 feet per second and is in some areas as great as 200 feet per second.

Profiles of temperature and salinity constructed from observations made at different seasons on a line extending southeastward from Montauk Point, Long Island, serve to illustrate both the seasonal cycle and the horizontal changes in the offshore direction.

Starting in midwinter the water column is virtually mixed from surface to bottom across most of the continental shelf (Figures 9 and 10). The temperature and salinity, however, both increase gradually in

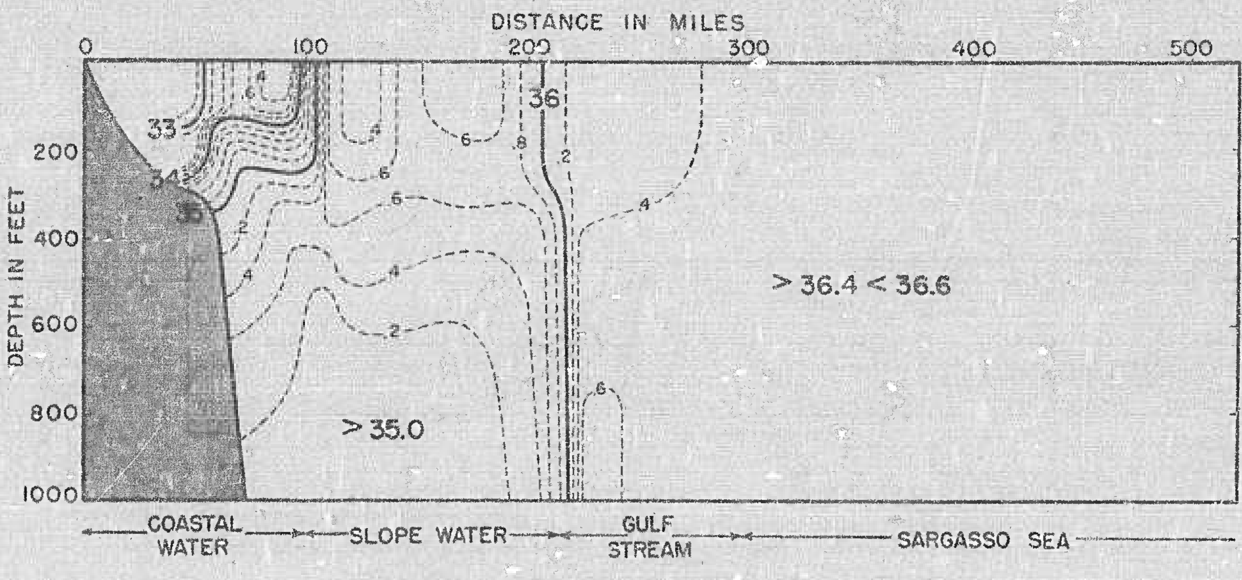

FIGURE 10. Salinity profile SE from Montauk Point in midwinter.

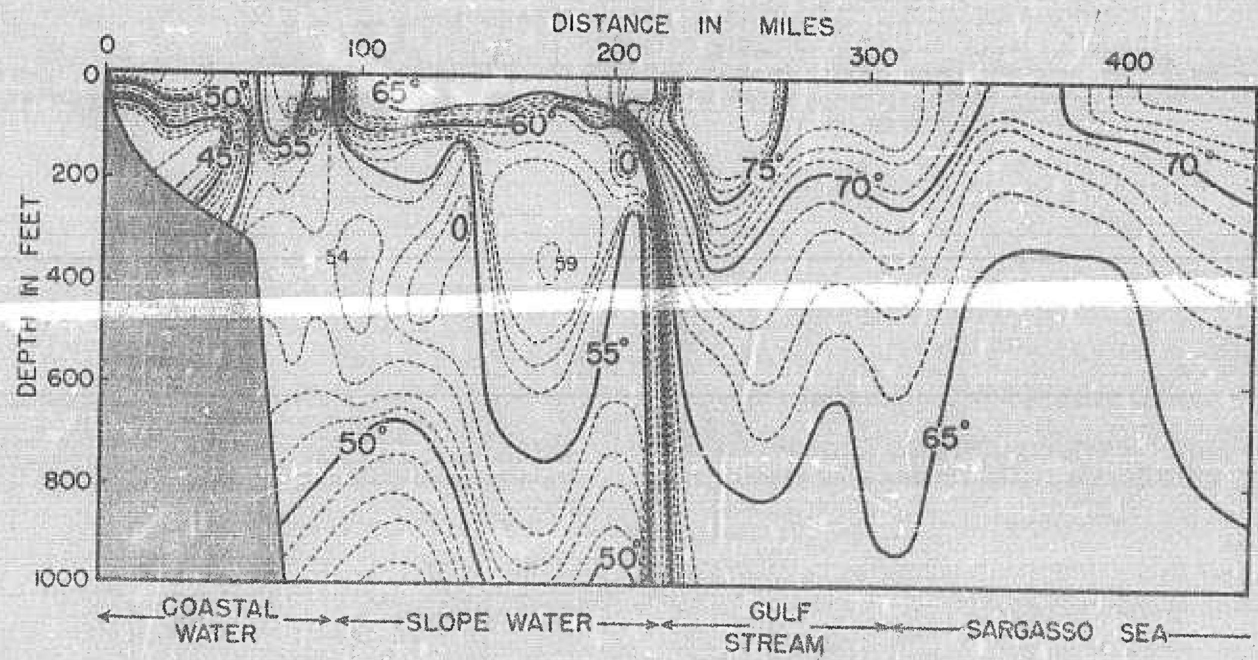

FIGURE 11. Temperature profile SE from Montauk Point in spring.

the offshore direction, and the isotherms and isohalines are on the whole quite parallel, the warmer water being the more saline. It is typical that near the edge of the continental shelf this increase is somewhat more rapid near the bottom, corresponding to the inshore component of the bottom water. At this season the crosscurrent density gradient, and therefore the strength of the current, is at a minimum, corresponding to the decreased land drainage of the winter months when much of the precipitation remains on the land in the form of snow and ice.

The spring conditions are illustrated by Figures 11 and 12. As the surface waters stabilize, because of vernal warming, surface salinities decrease, both because of decreased vertical turbulence and the spring freshets. Thus over the continental shelf the warmer

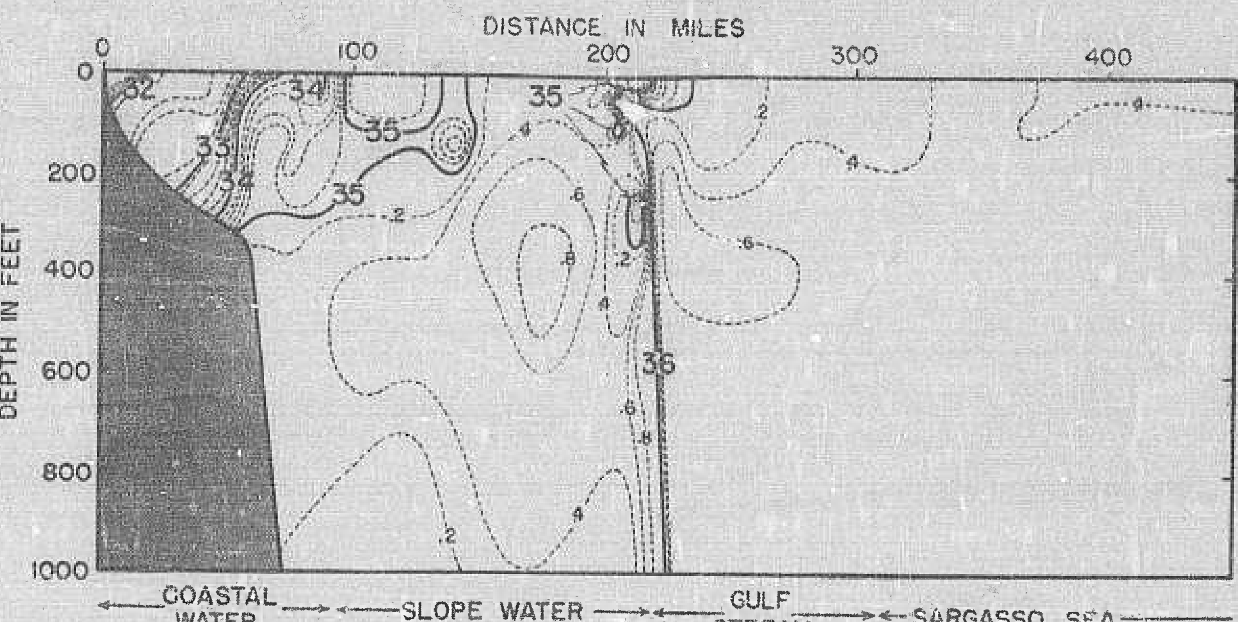

FIGURE 12. Salinity profile SE from Montauk Point in spring.

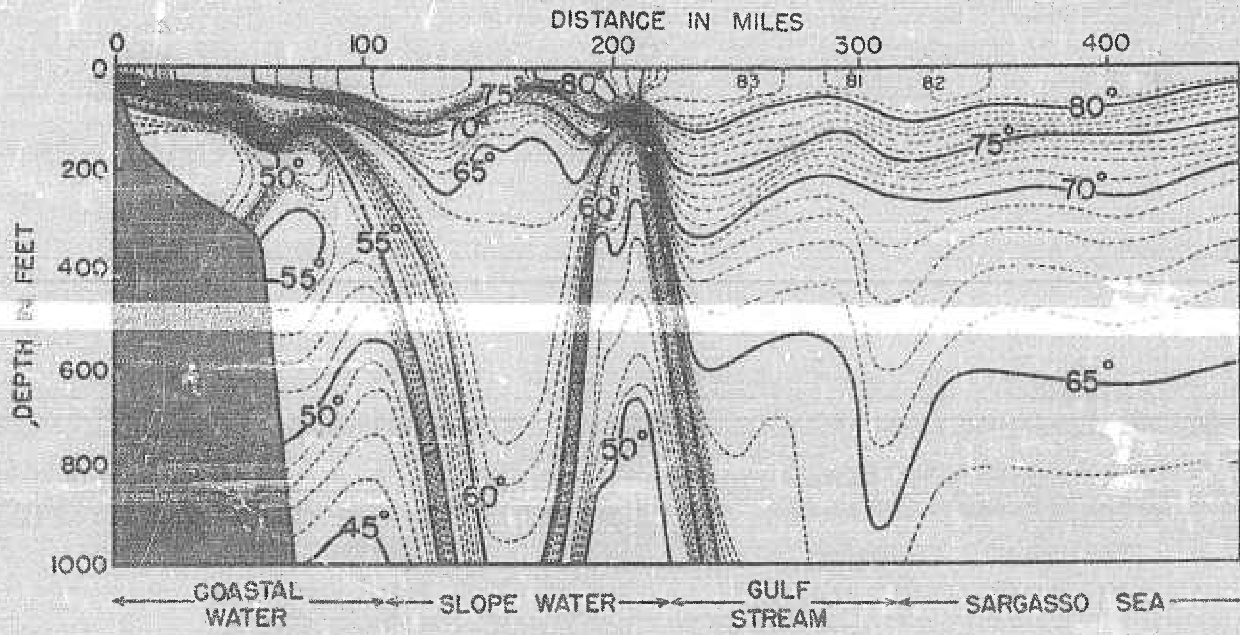

FIGURE 13. Temperature profile SE from Montauk Point in summer.

water becomes the less saline, which is the reverse of the situation in midwinter.

Vertical stability increases and consequently vertical mixing decreases until midsummer (Figures 13 and 14). Under such conditions lateral mixing is increased in the layer of greatest stability. This may partly explain the characteristic outward bulge of the isotherms at mid-depths over the continental slope. Here the isotherms and isohalines cross each other in a complex manner which is not well understood, but which is also at least partly caused by the strongest current, in this case southwestward, being concentrated near the 100-fathom contour. Thus near the offshore end of the coastal water section, cold water from the north is being carried into the profile more rapidly than further inshore.

During the autumn the coastal water, because of the prevailing cold and offshore winds, cools more

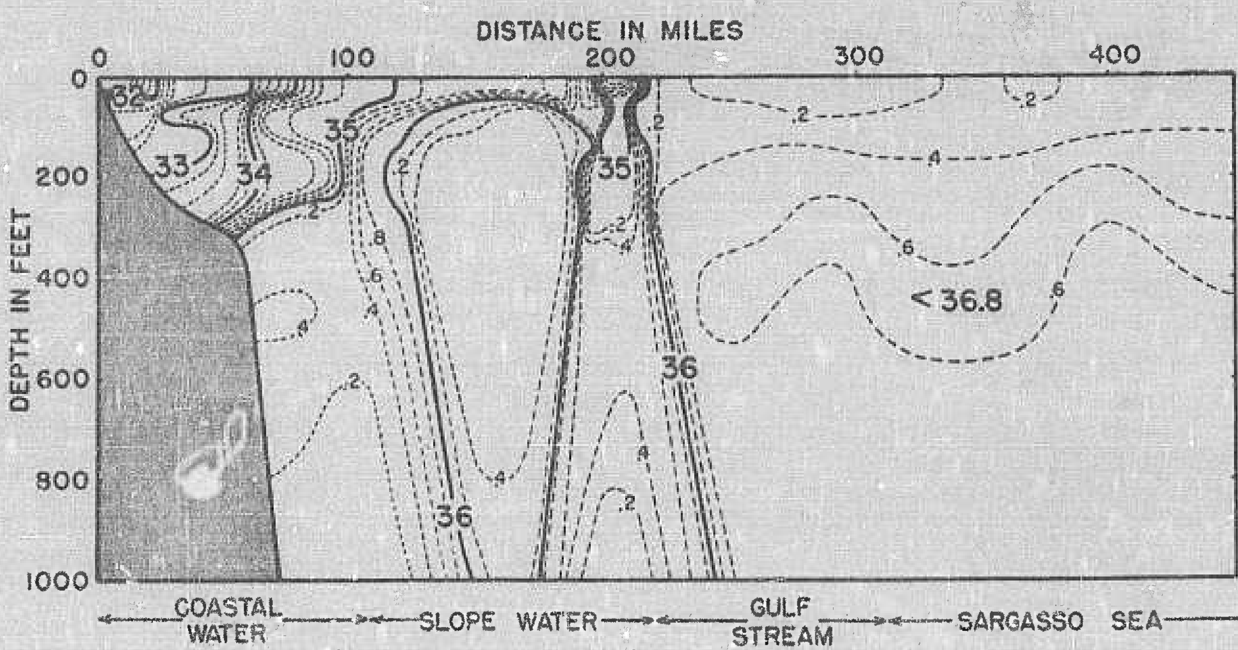

FIGURE 14. Salinity profile SE from Montauk Point in summer.

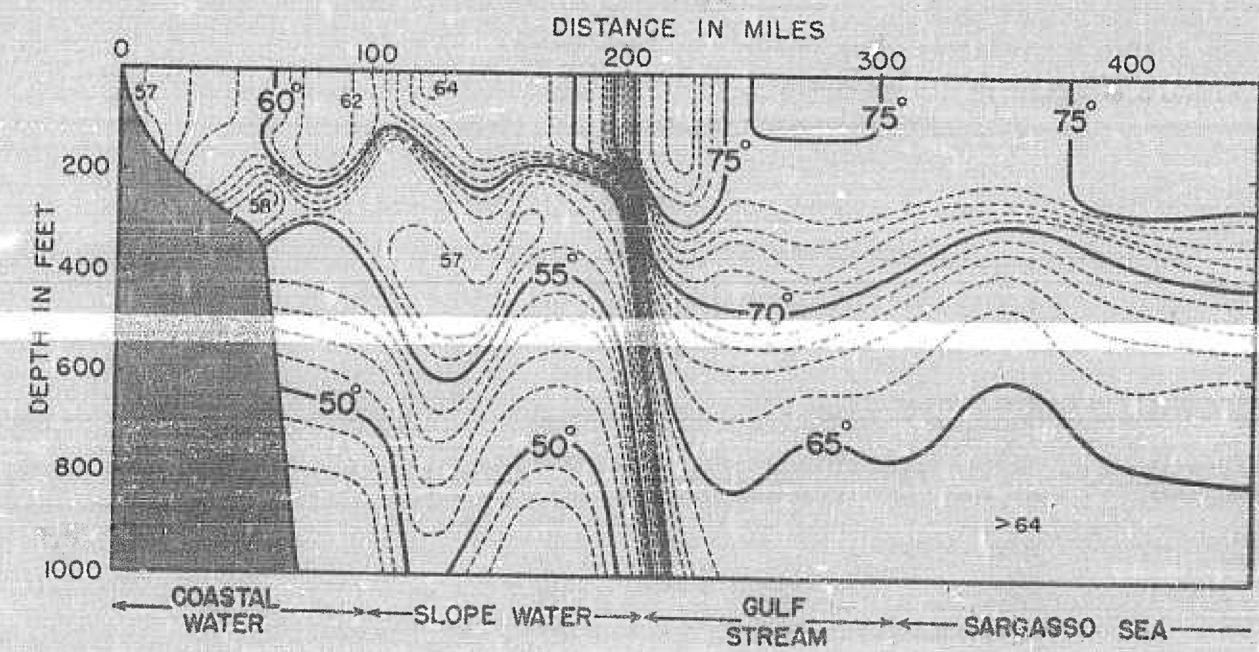

FIGURE 15. Temperature profile SE from Montauk Point in autumn.

rapidly than the offshore water. Thus positive gradients, both of temperature and of salinity, develop over the continental slope (Figures 15 and 16).

The major features described in these sections off Montauk Point could be made out in any profile across the continental shelf from Labrador to Florida. Except off Cape Hatteras and off southern Florida, along the whole of this coast the continental shelf is broad and well-developed. Fresh water is brought down to the sea by many rather evenly spaced rivers. Consequently a southward-flowing current, which tends to be strongest along the 100-fathom contour, follows the continental shelf southward and is only partially interrupted by such major irregularities as the Laurentian and Fundian Channels.

In Figures 17-19 the seasonal cycle at various points along this coastline is illustrated in the same manner

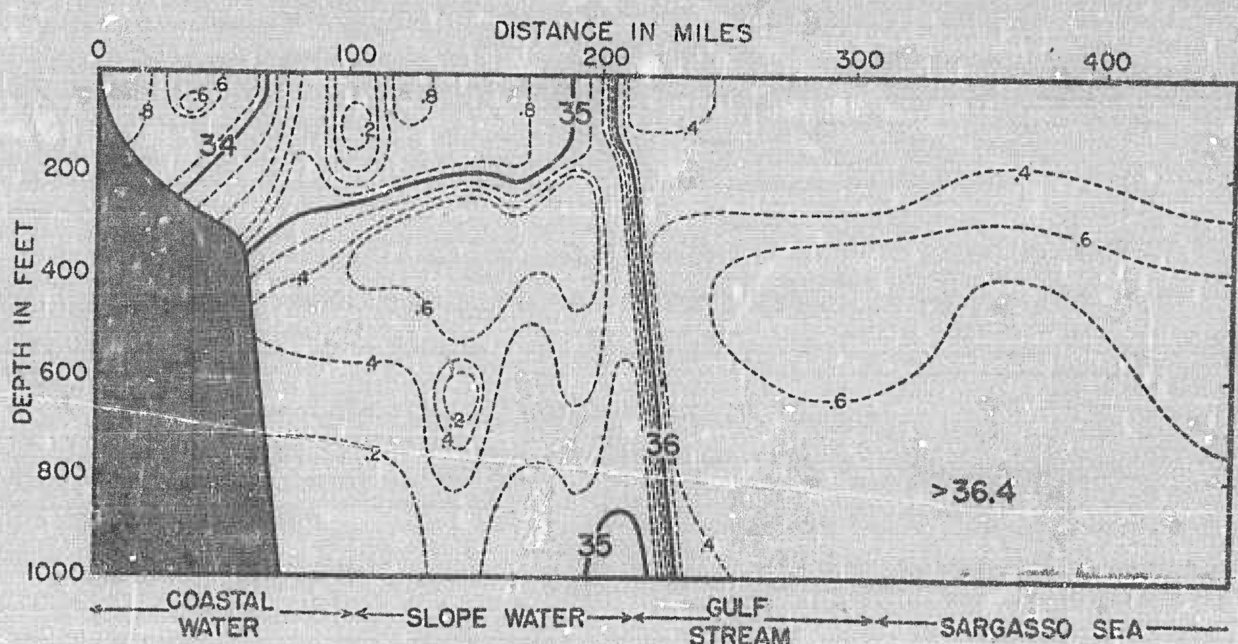

FIGURE 16. Salinity profile SE from Montauk Point in autumn.

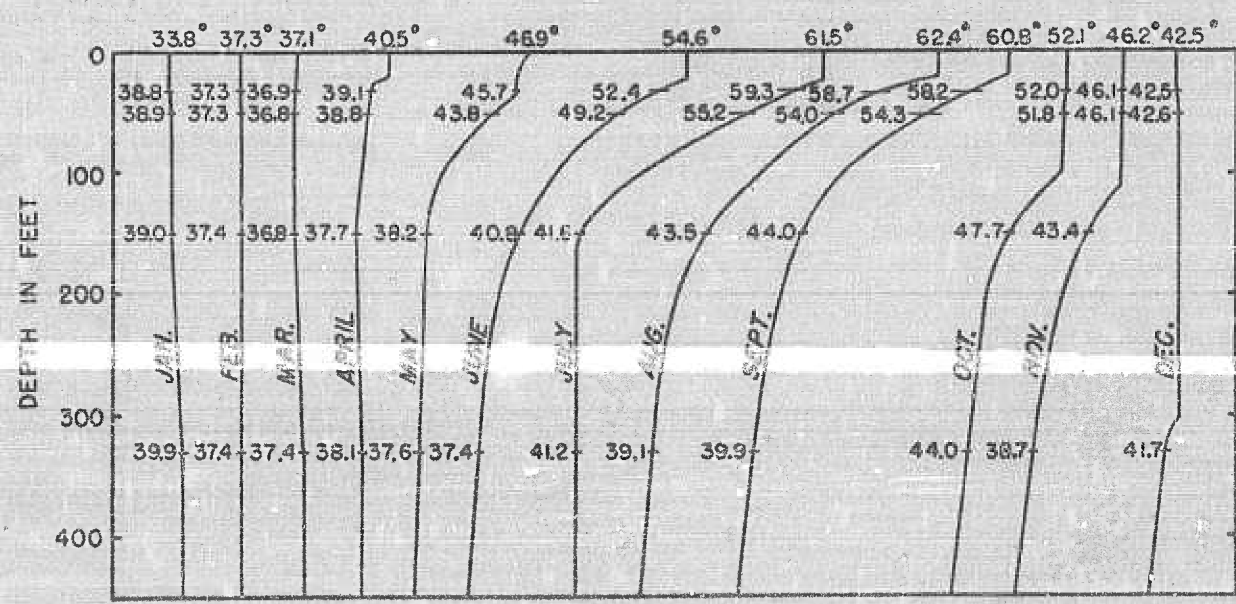

FIGURE 17. Seasonal cycle, Gulf of Maine, average monthly temperature-depth curves.

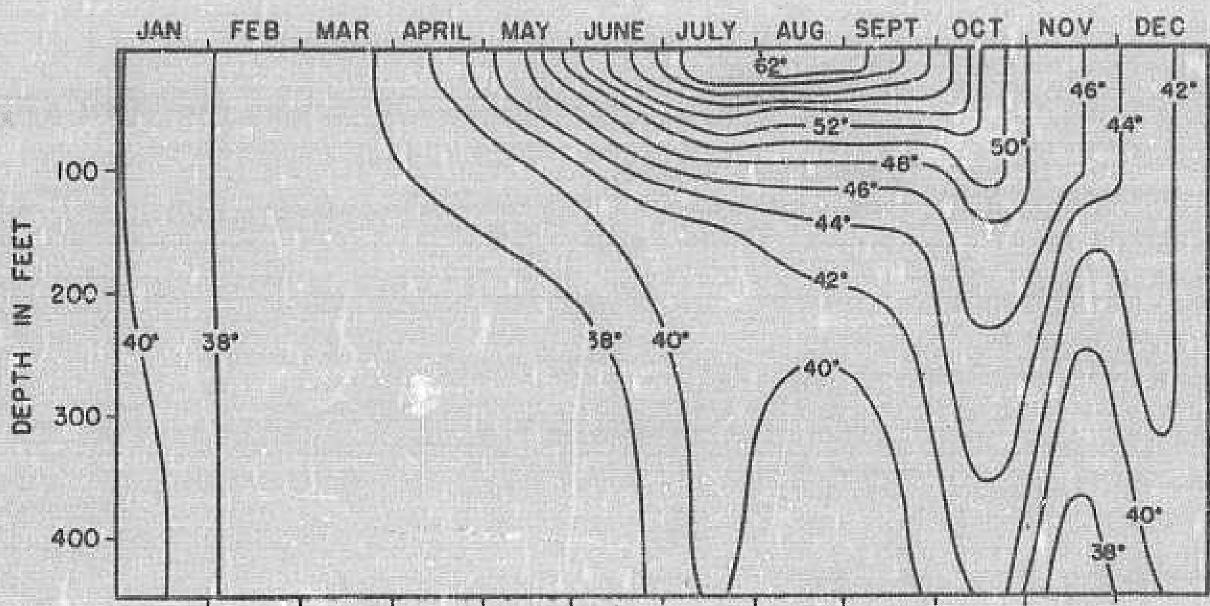

FIGURE 18. Seasonal cycle, Gulf of Maine, average monthly isotherms.

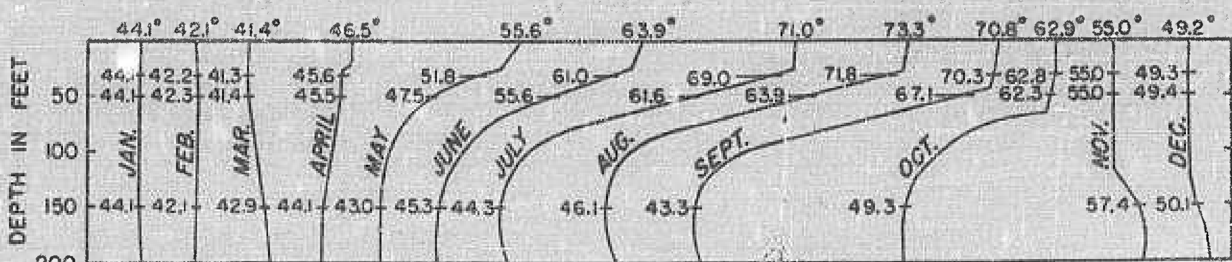

FIGURE 19. Average monthly temperature-depth curves in coastal waters between New York and Cape Hatteras.

as was used in Part 2 above (Figures 34 to 42, Chapter 5). A comparison between the two sets of diagrams serves to emphasize the relatively great stability of coastal waters as compared to offshore waters. Only in shallow areas where strong tidal currents occur is this not generally true.

In spite of the fact that the temperature-salinity correlation in coastal waters varies widely, both seasonally and geographically, with only a few exceptions the vertical temperature distribution controls the sound refraction pattern. As in deep water, this results from the fact that in layers where the salinity is changing most rapidly with depth, temperature does likewise. Only when the salinity gradients are unusually strong is the BT lowering likely to be misleading from the acoustical standpoint. For example, Figure 20A shows the vertical distribution of temperature and salinity at the mouth of the Baltic Sea in May 1937. Here relatively fresh and warm Baltic water overlies colder and more saline Atlantic water, and the depth of the thermocline more or less coincides with the depth of the maximum salinity gradient. A BT reading would indicate sharp downward refraction with very short echo ranges. The salinity gradient, however, partly compensates for the temperature effect. Both together are equivalent acous-

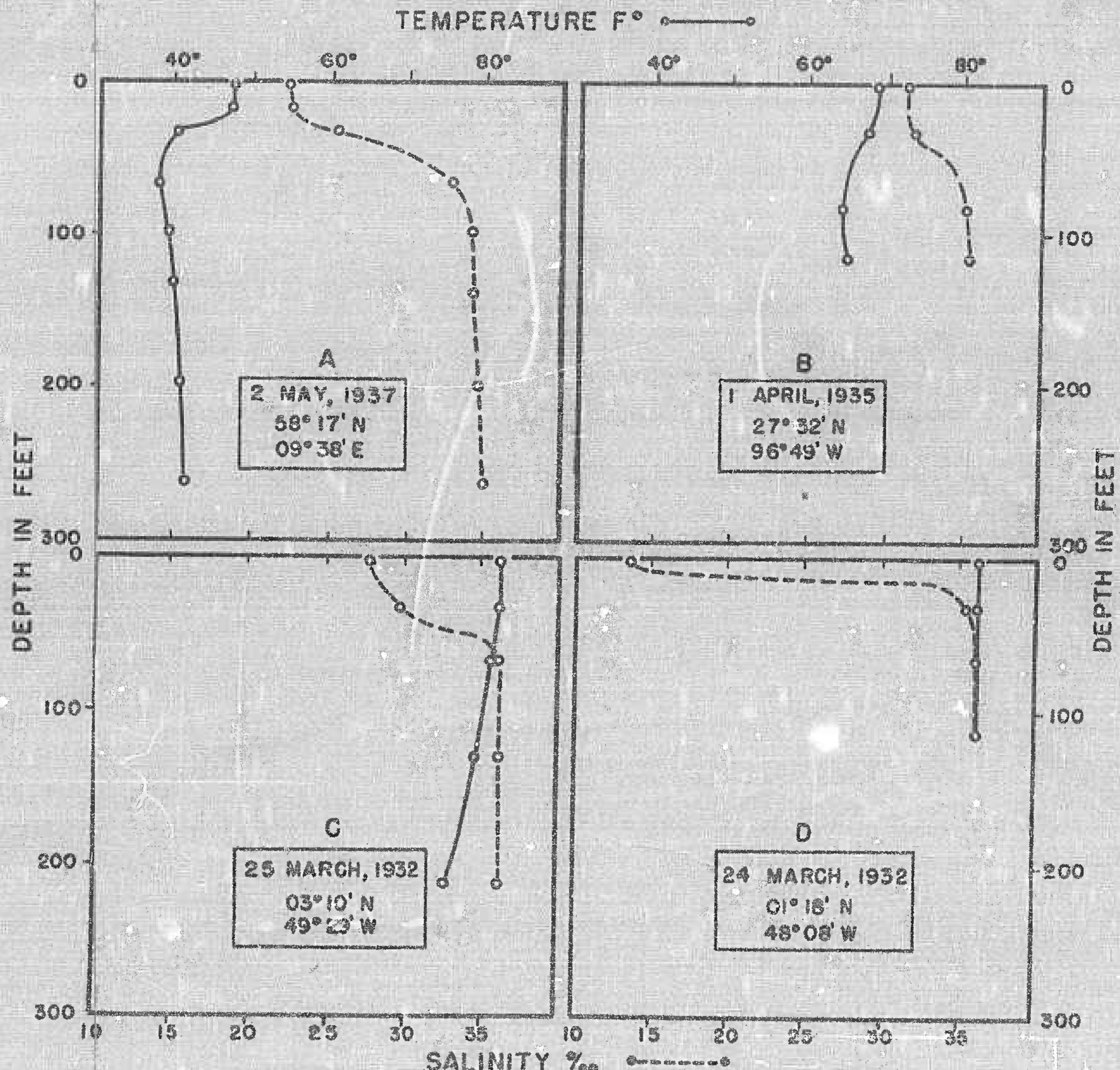

FIGURE 20. Acoustically critical temperature and salinity gradients in coastal waters.

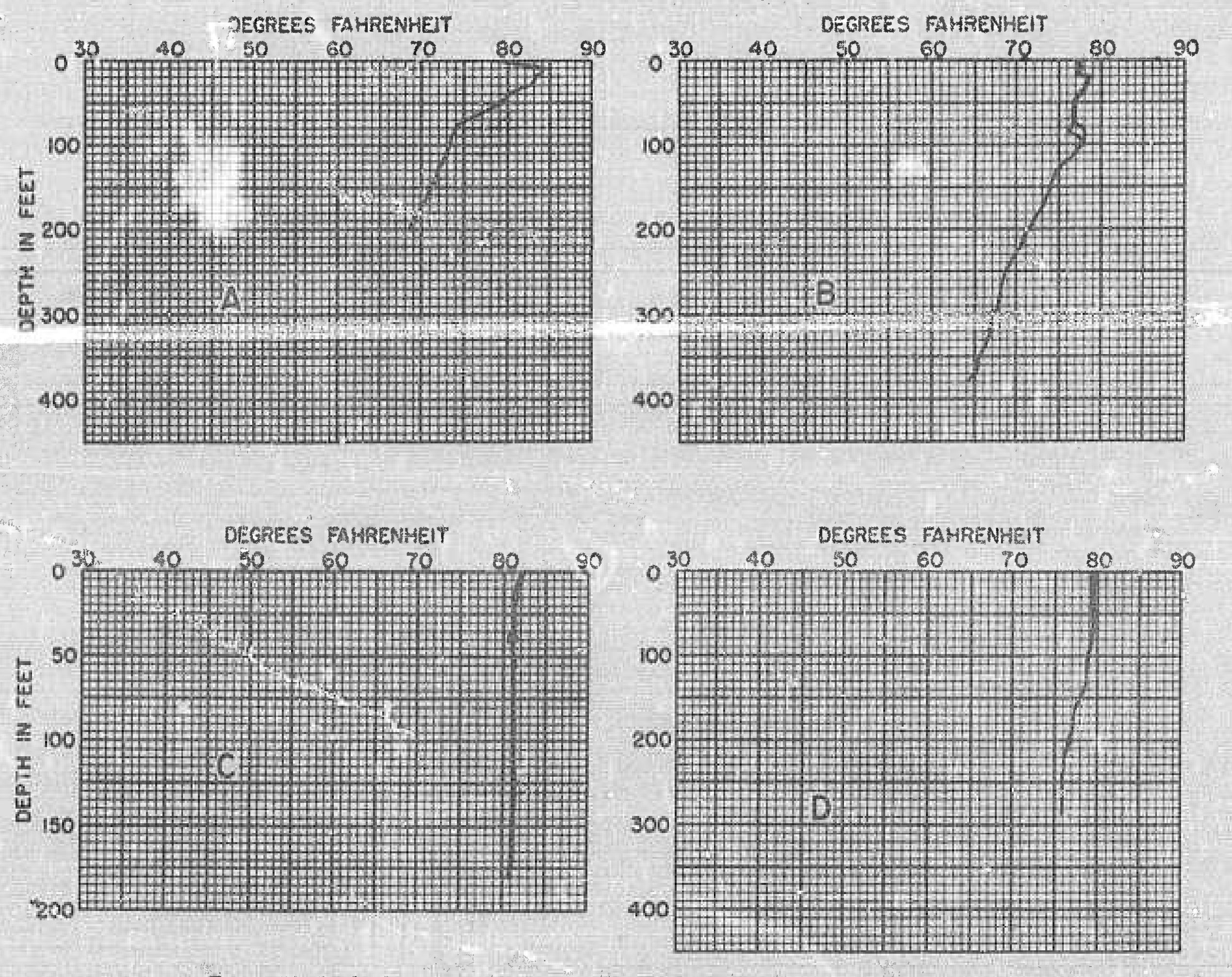

FIGURE 21. Bathythermograms from probable areas of critical salinity gradients.

tically to a temperature decrease of about 1 degree in the upper 60 feet, and the predicted range is medium. Thus it is apparent that in extreme cases salinity gradients can be important, but that a very large salinity gradient will be compensated by a relatively weak temperature change. In Figure 20B, which shows a more typical temperature-salinity distribution in that the salinity gradient is not so extreme, a reasonably accurate prediction can be made from temperature alone.

Sometimes, however, strong salinity gradients occur when there is little or no vertical change in temperature. Examples are shown in Figures 20C and 20D, which represent conditions off the mouth of the Amazon. The salinity gradient in Figure 20C is highly significant since it is not compensated by a temperature change. In this case there will be sharp upward refraction, and it is unlikely that a vessel with conventional (non-tilting) sonar gear will be able to get contact on a submarine below the fresh surface layer.

Figure 20D differs from the preceding one in that the salinity gradient is probably largely confined to a shallow surface layer above projector depth. When this is the case, it obviously will not interfere with echo ranging. It is difficult to say how common it is to find salinity gradients of this sort because oceanographic water samples have seldom been spaced at close enough depth intervals to show the complete vertical structure. However, there are many examples of bathythermograms such as the one in Figure 21A, in which a very shallow positive temperature gradient indicates the existence of a fresh surface layer too thin to affect echo ranging.

The remainder of Figure 21 shows other examples of bathythermograms from areas where strong salinity gradients are ordinarily found. Their existence is obvious in Figure 21B, but in C and D, taken near

the Amazon in areas where it is almost certain that such gradients occurred, there is nothing in the bathythermograms to indicate their presence.

In summarizing the acoustic effects of salinity gradients, it is apparent that there are two main factors to be considered: (1) the depth of the gradient, since it is not important if it is above projector depth; (2) the amount of change in salinity with respect to temperature changes. The worst situation from the standpoint of echo ranging occurs when the water column is essentially isothermal, because then not only is the salinity gradient most effective but also the bathythermograms are most misleading. This condition is quite common in the tropics. In temperate and arctic regions the outflow from rivers is likely to be warmer than the ocean water in summer and colder in winter. Therefore it is only for short periods in the spring and autumn that salinity gradients are likely to occur without corresponding temperature gradients.

Since density currents must flow parallel to coasts, the water of reduced salinity which is formed near the mouths of rivers tends to spread along the coast instead of flowing out to sea. The influence of a large river may be noted hundreds of miles away. Thus in the Gulf of Mexico a fresh surface layer extends westward from the mouth of the Mississippi, and the freshening influence can be detected, particularly in spring, beyond Galveston (Figure 20B). In areas of adequate rainfall, therefore, continuous bands of water of low salinity are formed along the coasts, and the influence of the rivers seldom extends far out to sea except near the equator where Coriolis force is much reduced.

Minor and temporary cases where the refraction is controlled by vertical salinity gradients can be found at New London, Connecticut, where the outflow from the Thames River sometimes overlies virtually isothermal water of about the same temperature which has been mixed by the strong tidal currents of the narrow entrances to Long Island Sound.

At the edge of the continental shelf, where near the surface the relatively fresh coastal water tends to overlie more saline water, one would expect occasionally to find situations where vertical salinity gradients controlled the refraction. No pertinent observations have been uncovered, but since the band where the right conditions prevail is narrow, the oceanographic stations do not usually come at just the critical point.

9.3 BOTTOM STRUCTURE

It was pointed out in the introductory statements that both bottom topography and the composition of sediments are important in echo ranging. Whether or not it is an advantage for an echo ranging ship to work over a bottom that is a good reflector of sound depends entirely on the direction in which the sound is reflected. A smooth, hard bottom that reflects sound on ahead is ideal, and ranges will be nearly as good as in deep water with perfect temperature conditions. But if bottom irregularities intercept sound at nearly right angles, reflecting it back toward the sound source, the result is reverberation and skip distances. The size of the irregularities does not need to be very great. Stones or ripple marks only 3 or 4 inches high will raise the reverberation level of supersonic gear markedly. Hence stony, rocky, and coral bottoms are almost always poor from the echo ranging standpoint because of their roughness. Sand bottoms are usually good because they are not only good reflectors but are also generally smooth. Occasionally they may be poor, however, when there is enough current over the bottom to produce ripple marks, and there is some evidence that a particular sand bottom may vary considerably in this respect according to the way it is disturbed by tides and storms.

The manner in which these generalizations fit the observed facts is illustrated by a recent analysis[1] of all the observed maximum ranges and suitable acoustical measurements in shallow water. It was found that for all refraction patterns over rock and coral bottoms, ranges were less than 1,500 yards 60 per cent of the time and averaged about 1,000 yards. Maximum ranges over sand were less than 1,500 yards only 20 per cent of the time and averaged 2,500 yards, while over sand and mud the ranges were less than 1,500 yards 30 per cent of the time and averaged about 2,200 yards. Over soft mud bottoms, results varied according to the refraction pattern as in deep water.

The methods of correlating bottom types with acoustic phenomena were discussed in some detail in Chapter 2, as well as the principles used in constructing bottom sediment charts for tactical use by naval forces. This work can be understood more clearly, however, by considering briefly how the different bottom types are produced in the first place and how various oceanographic factors affect their distribution.

Marine sediments as a whole are a very heterogeneous collection of all the materials carried into the sea or produced in it which are heavy enough to sink to the bottom and inert enough so that they have not dissolved or decomposed into soluble substances. A fairly large proportion of the sediments is derived from land. Direct erosion of the shore line by wave action is one of the most important sources of such material. River drainage depositing its load of silt in the sea is also important, as is glacier movement. A less obvious but certainly significant source of marine sediments is air-borne dust derived from arid regions and from volcanic explosions. The sea produces some of its bottom sediments, for the most part by biological processes (shells, coral) but also by precipitation of inorganic chemical substances from sea water and by accumulation of the products of submarine volcanic activity. Taken altogether these are probably the most important sources of marine sediments although there are a great many other contributing agencies of minor significance.

The sea is continually moving and reworking the loads of sediment brought into it. The physical force of waves and currents carries the smaller particles along, grinding them against each other and against larger stationary objects on the bottom. The eroding effect of such action is obvious on any rocky beach, where the smaller pebbles are rounded and the surface of the larger rocks and boulders are worn smooth. The tendency then is for boulders to be transformed gradually over long periods of time into mud. Over similarly long periods chemical activity is also important, dissolving and decomposing sedimentary materials. Some minerals are far more subject to chemical as well as physical dissolution than others. The hardness and inertness of quartz, for example, is responsible for its abundance (in the form of sand) on the continental shelf. It remains behind while other less stable substances are reduced to a finer state and carried further out to sea.

Transportation of sediments obviously depends on both particle size and the speed of the current. Suppose, for example, a swift-flowing river delivers into the sea a load of sediment ranging in particle size from fine mud to sand. In the slower moving ocean currents the sediment will settle gradually, the larger particles going to the bottom more quickly, so that they are not carried as far from the source as the smaller sizes. Thus, speaking in broad terms and neglecting many local variations, sediments tend to be coarse near shore, grading to fine mud in the deep oceanic basins.

Particles too large to be carried completely in suspension may be lifted momentarily and carried for a short distance before they settle back to the bottom. Still larger particles may be rolled along. And finally, a certain amount of transportation may occur in the absence of currents. The familiar terrestrial phenomenon of landslides has its counterpart on the sea floor. Mud slides are a fairly common phenomenon wherever silt settles on a sloping bottom. Because the buoyancy of the water makes the friction between the mud particles much less than it would be in an aerial environment, mud slides may occur on very slight slopes.

The type of bottom that occurs in any particular area depends on the interaction of the factors that have been mentioned—the kind of sedimentary materials available, the way they have been worked over by marine agencies, and the way their deposition is affected by local currents. It is possible to tell a great deal about the bottom simply by examining a chart that shows the shore line and bottom topography, since these are indicative of both the character of the materials and the current pattern. Thus it is natural to find mud deposits off the mouth of a large river, or a smooth, sandy bottom lying off a low, sandy coast. Or, if the shore line is irregular, with headlands and estuaries, the bottom is likely also to be variable both as to topography and bottom type. It probably will be rocky off the headlands, in the mouths of rivers, and around submerged reefs where the currents are strong enough to scour the bottom and carry away finer sediments. On the other hand, small basins will collect deposits of sand or mud.

Further offshore, topographic features of the bottom are associated with similarly characteristic sediment types. Submarine ridges or sharp changes in depth such as occur at the edge of the continental shelf are nearly always accompanied by currents that expose rock surfaces or at least ripple the sand sufficiently to make echo ranging difficult. Offshore banks with their strong rotary tidal currents also show pronounced ripple marks, often at depths of nearly 100 fathoms. Currents can affect submarine topography as well as be affected by it, since a current strong enough to transport sand must ultimately deposit it somewhere, generally in the form of a ridge or bank at the current's edge.

In the tropics, coral reef formation is often the

dominant feature of submarine topography in shallow water, and in such areas high reverberation makes echo ranging very difficult. Of similar acoustical quality is the rough, rocky bottom in the neighborhood of islands produced by submarine volcanic eruptions.

Bottom topography and structure have always been of considerable interest from the standpoint of navigation, and most coastal areas have been surveyed at one time or another with varying degrees of accuracy and completeness. The depth of water has been measured by sounding leads and more recently by acoustic fathometers which provide far more complete data. Bottom type was largely determined from small samples collected by a cup or tube on the end of the sounding lead or by grease smeared in a depression on its lower end.

Oceanographic expeditions have also obtained a considerable amount of information about bottom type and topography. In general, larger samples of bottom have been collected than in the case of navigational surveys. Scientific description of bottom structure requires large samples. Since often the bottom is composed of widely different sizes and kinds of fragments, a small sample can be very misleading. For this reason oceanographers have used various types of dredges, tubes, and containers with jaws that snap shut on contact with the bottom. More recently the underwater camera referred to in a previous chapter has been used extensively in such studies. It takes a picture of about 50 square feet of the bottom and shows many details of bottom structure and small-scale topography that are valuable supplements to the information obtained by sampling devices. Examples of bottom pictures are shown in Figures 22-24.

Charts of bottom topography can be prepared in very great detail by using modern recording fathometers. It is a far more laborious task to sample the bottom adequately for charts of sediment types. This has been done in a few local areas for scientific purposes and in connection with the acoustical tests described in Chapter 2. In other places, where only government surveys have been made, the bottom notations on the charts are not completely adequate for acoustical purposes. Where soundings are not closely spaced, it is necessary to decide whether or not a particular area is divided into patches or is continuous, and what its areal extent and probable boundaries may be. Thus it is necessary to depend a great deal on general oceanographic and geological knowledge about the kind of sedimentary materials available in the region and how they might be deposited according to local currents and bottom topography.

FIGURE 22. Photograph of a smooth, sandy bottom.

In order to understand more fully just what the requirements are for a bottom sediment chart, the chapter ends with a discussion of the material collected by the government surveys and how it has been used for purposes of subsurface warfare.

For the continental United States and its possessions, which have been surveyed by the Coast and Geodetic Survey, the data are unusually complete. In addition to the bottom notations on the printed charts, a great many of the samples have been preserved, and access may be had to the original field data sheets. These sheets are drawn on a much larger scale and contain many more soundings and bottom notations than appear on the finished printed charts. Such information was used for drawing the boundaries between the different bottom types which appear on the wreck charts for the Atlantic and Gulf Coasts, and for bottom sediment charts covering areas in the Philippine Islands.

In the case of foreign areas, it is necessary to consult the archive files of the Hydrographic Office, not only for their latest edition of any particular chart, but also for all the foreign editions from which it was compiled. There is a tendency on the newer charts to

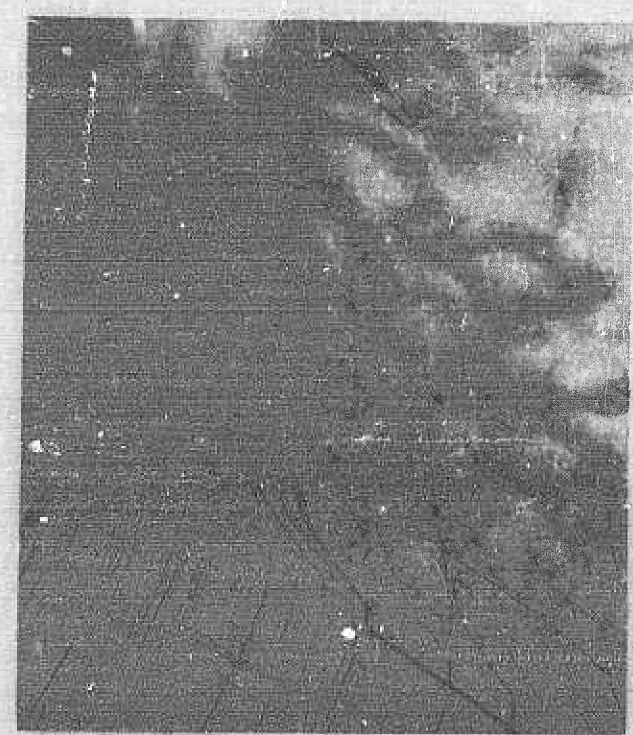

FIGURE 23. Photograph of a rough, sandy bottom showing ripple marks caused by currents.

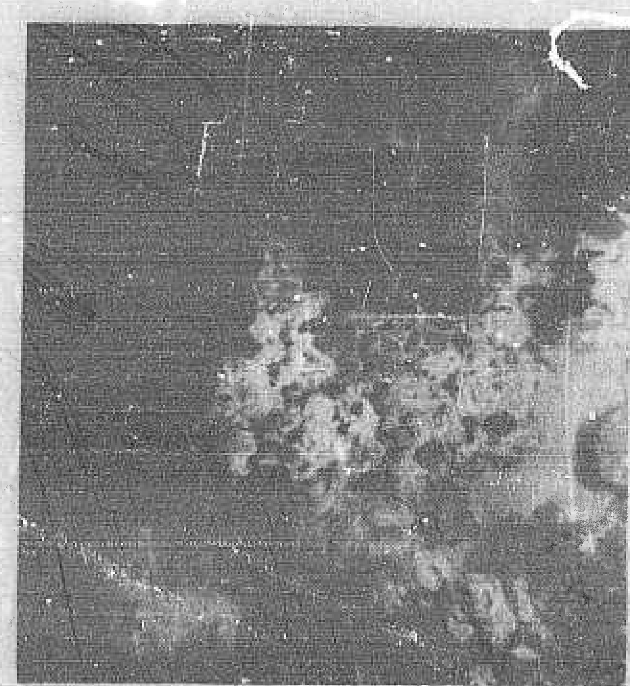

FIGURE 24. Photograph of a coral bottom.

omit bottom notations and frequently earlier surveys may furnish additional information.

The British surveys of regions outside their own coastal waters are excellent, particularly in the Far East, and the French and Germans have also done good work off their more limited foreign possessions. The Japanese Hydrographic Office has published many detailed surveys of the Home Islands and the adjacent Asiatic coast. Data from these latter charts were carefully examined from a geological and topographic point of view, and the bottom information was found to be in line with what might be expected. The charts compiled from them are believed to be fully as accurate as those compiled from other sources.

The Archives of the British Admiralty have also been available and photostats of field data sheets as well as of earlier surveys have been furnished for critical areas—material which was not available in Washington.

Certain conditions must be borne in mind when charts of the bottom are drawn from information on the navigation charts and not from actual material. If the notations on the charts were everywhere accepted at their face value, many mistakes would result. As stated before, the samples were taken as an adjunct of sounding with a lead, and a very small amount of material was obtained. Several misconceptions may arise as a result. First, there is a tendency to overemphasize the mud areas and make them appear more numerous and larger than they really are. Any bottom that feels at all soft or a sample which looks dark colored and oozy when wet is generally called mud by hydrographers. A mechanical analysis of the material, in many cases, would show this sediment to be sand and mud. Second, any bottom which feels hard to the leadsman and from which no sample is obtained, is apt to be labeled rocky or coral, depending on the latitude. In most cases, this is correct, but stones or small coral fragments, in some cases, would have the same "feel." Third, as the sampling apparatus can pick up only a small amount of material consisting of the smaller particles, only the gravel and sand fractions would be brought to the surface over some stony bottoms. Adequate dredge samples and also photographs have shown that gravel bottoms usually have numerous stones. Consequently, except in glacial areas, it was decided to classify all gravel bottoms as stony. The same applies to such classifications as pebbles and shells, which usually occur in conjunction with stones. Fourth, the term clay suggests that the bottom has been somewhat compacted so that it will reflect sound better than

ordinary mud but probably not as well as a sand bottom. Since sand and mud is also an intermediate classification, it is used for clay. Then there are cases in which two or more bottom symbols are given, such as rock and sand. The acoustical significance of the rock portion is greater than that of the sand, and the sediment is so classified.

These, then, are the principles used in constructing bottom sediment charts from information that admittedly was not so adequate as might have been desired. No chart is ever perfect, and the navigation charts themselves are subject to constant improvement. The bottom sediment charts depend on the hydrographic survey which preceded them, together with whatever geological information can be brought to bear. Obviously, a better bottom sediment chart can be constructed from a detailed, large-scale survey of an important approach than from a region where the soundings are widely scattered. Neither one is so accurate as a chart made from an area from which bottom samples and photographs have been obtained. Also it is probably true that at present the bottom sediment charts are more accurate from the geological standpoint than they are as predictions of echo ranging conditions. If greater accuracy is to be attained in predictions for foreign areas, further work in underwater sound should be carried out over all types of bottom where it is possible to take samples and photographs, so that all the unknowns may be investigated simultaneously.

GLOSSARY

AMBIENT NOISE. Noise present in the medium other than target and own-ship noise.

BOURDON TUBE. A flattened curved tube which tends to straighten out under internal pressure, used as the driving element in pressure temperature gauges.

BT. Bathythermograph.

BUOYANCY. As used in this volume, the net buoyancy, or the difference between the weight of the water displaced by a vessel and the weight of the vessel.

CONVECTION CELL. A vertical section of the isothermal mixed layer bounded by cool currents descending from a convergence and warm currents rising to a divergence.

DENSITY GRADIENT. Change of density with depth.

ISOBALLAST LINES. A set of lines, on the SBT chart, each starting from a set of selected points on the temperature scale and passing through all points for which the net change in buoyancy, resulting from changes in water temperature and depth is zero for a submarine of a given compression.

ISOHALINES. Lines drawn through all points having the same salinity.

ISOTHERMS. Lines drawn through all points having the same temperature.

LAYER DEPTH. The depth of the mixed surface layer.

LAYER EFFECT. Reduction in the echo and listening ranges on a submarine located within or beneath a thermocline.

MIXED LAYER. The isothermal layer occurring at the water surface.

REVERBERATION. Sound scattered diffusely back toward the source, principally from the surface or bottom and from small scattering sources in the medium such as bubbles of air and suspended solid matter.

REVERSING THERMOMETER. A deep-sea recording thermometer: the temperature reading at the desired depth is preserved by overturning the instrument to break the mercury column.

SALINITY. Number of grams of salt per thousand grams of sea water, usually expressed in parts per thousand.

SALINITY GRADIENT. Change in salinity with depth, expressed in parts per thousand per foot.

SBT. Submarine bathythermograph.

SHADOW ZONE. Region in which refraction effects cause exclusion of echo-ranging signals.

SINKING CENTERS. Subarctic regions where strongly saline surface water of tropical origin sinks through the colder, but less saline underlying layers.

STABILITY. The resistance to overturn or mixing of the water column, resulting from the presence of a density gradient.

STATION. A set of pairs of thermometer readings taken in a specific location at approximately 100-meter depth intervals, along with a corresponding set of water samples analyzed for salinity. A station is "occupied" when these readings are procured.

TARGET ASPECT. Orientation of the target as seen from own-ship.

TEMPERATURE GRADIENT. Change of temperature with depth, expressed in degrees F per foot.

THERMOCLINE. A layer of water in which temperature decreases with depth; a negative temperature gradient.

UPWELLING. Rise of the main thermocline, and the underlying deep-water mass, toward the upper levels as the warm surface water is swept away by the winds.

VELOCITY GRADIENT. Rate of increase in the velocity of sound with increasing water depth.

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CONTRACT NUMBERS, CONTRACTORS, AND SUBJECT OF CONTRACTORS

Contract Number	Name and Address of Contractor	Subject
OEMsr-20	The Trustees of Columbia University in the City of New York	Studies and experimental investigations in connection with and for the development of equipment and methods pertaining to submarine warfare.
OEMsr-1131	The Trustees of Columbia University in the City of New York	Conduct studies and investigations in connection with the evaluation of the applicability of data, methods, devices, and systems pertaining to submarine and subsurface warfare.
OEMsr-31	Woods Hole Oceanographic Institution Woods Hole, Mass.	Studies and experimental investigations in connection with the structure of the superficial layer of the ocean and its effects on the transmission of sonic and supersonic vibrations.
OEMsr-30	The Regents of the University of California Berkeley, California	Maintain and operate certain laboratories and conduct studies and experimental investigations in connection with submarine and subsurface warfare.
NDCrc-40	Woods Hole Oceanographic Institution Woods Hole, Mass.	Studies and investigations in connection with the oceanographic factors influencing the transmission of sound in sea water.
OEMsr-287	President and Fellows of Harvard College Cambridge, Mass.	Studies and experimental investigations in connection with (i) the development of equipment and devices relating to subsurface warfare.
OEMsr-1046	Massachusetts Institute of Technology Cambridge, Mass.	Studies and experimental investigations in connection with (1) underwater sound transmission and boundary impedance measurements; (2) ship sound surveys at high frequencies; (3) development of devices for the control of underwater sounds; and (4) development of intense underwater sound sources for special purposes.

[redacted]

SERVICE PROJECT NUMBERS

The projects listed below were transmitted to the Executive Secretary, National Defense Research Committee, NDRC, from the War or Navy Department through either the War Department Liason Office for the NDRC or the Office of Research and Inventions (formerly the Coordinator of Research and Development), Navy Department.

Service Project Number	*Subject*
NS-140 Ext.	Acoustic properties of the sea bottom
NS-140	Range as function of oceanographic factors
NS-141	Acoustic properties of wakes
NS-208	Sonar-surface and submarine bathythermograph instruction program

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The subject indexes of all STR volumes are combined in a master index printed in a separate volume. For access to the index volume consult the Army or Navy Agency listed on the reverse of the half-title page.

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